CERN

**CERN and Fermilab** (top and bottom, respectively) in the late 1970s, around the time that, according to bibliometric data, Europe took the lead from the United States in experimental particle physics. Figure 1

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# The shifting balance of power in experimental particle physics

'Bibliometrics'—the analysis of publication and citation data—indicates that Europe has taken the lead from the US in experimental high-energy physics, which raises the question of how the US should respond.

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For 30 years after the second world war, the United States dominated experimental particle physics. This dominance was particularly pronounced during the 1950s, when the leading US machines dwarfed those in Western Europe, while ostensibly equivalent facilities in the Soviet Union posed little threat. The 1960s witnessed the beginning of a European challenge from the new Proton Synchrotron at the joint European laboratory CERN near Geneva and from various smaller machines in national laboratories such as DESY at Hamburg. Yet despite a broad similarity in the research facilities available on either side of the Atlantic, the major discoveries of the 1960s—the $\Omega^-$, the two types of neutrino, CP violation and deep inelastic electron scattering—all came from the US.

Not until 1973 did the Europeans record their first important postwar accelerator-based discovery—the neutral weak current, which provided vital evidence to support the new unified theory of electroweak interactions, and which led to Steven Weinberg, Abdus Salam and Sheldon Glashow receiving a Nobel Prize. (Earlier particle-physics discoveries in Europe—of the pion and strange particles, for example—had involved cosmic-ray rather than accelerator experiments.) Yet in the period of revolutionary change from 1973 to 1978, American accelerators reigned supreme. The $J/\psi$ particle was discovered simultaneously at the Brookhaven Alternating Gradient Synchrotron and at SPEAR, the electron–positron collider operated by the Stanford Linear Accelerator Center, rather than at their European counterparts, the CERN Proton Synchrotron and DORIS, the collider at the German national particle-physics laboratory DESY. Likewise, particle physicists first observed the $\tau$ heavy lepton and charmed mesons at SPEAR rather than DORIS. The $\Upsilon$, which like the $J/\psi$ *could* have been found at the Intersecting Storage Rings at CERN, was instead discovered at Fermilab. Finally, it was SLAC that discovered parity violation in inelastic electron scattering, a crucial test of the new electroweak theory.

Since 1979, however, US contributions have declined rapidly. As we shall see, the original Fermilab 500-GeV accelerator has been outclassed by the similar-energy Super Proton Synchrotron at CERN (see figure 1); PETRA, the electron–positron collider completed at DESY two years ahead of PEP, the equivalent facility at SLAC, was first to explore its energy range, just as SLAC had "scooped the field" five years earlier with SPEAR, which started a year ahead of its German rival DORIS; last, with the scrapping of the Isabelle (later CBA) project at Brookhaven, CERN's new proton–antiproton collider has had the field of high-energy hadron collisions to itself, successfully exploiting this with the Nobel Prize-winning discoveries of the W and Z particles.

This shift in the balance of power has not gone unnoticed. Since 1980, American researchers have voiced growing concern about the loss of their lead and about the future of high-energy physics in the United States. Couching their arguments in somewhat nationalistic terms, they have lobbied for the construction of a huge Superconducting Super Collider to explore the 1-TeV energy region. The intention is that SSC be[1] "*the* forefront high-energy facility of the world" and thus "assure a forefront *United States* high-energy-physics program into the 21st century" (emphasis added). The appeal to nationalistic sentiments is particularly well illustrated in the following statement (PHYSICS TODAY, March 1985, page 34) by Glashow and Leon Lederman, two leading US particle physicists:

> More and more, American accomplishments either recede into the

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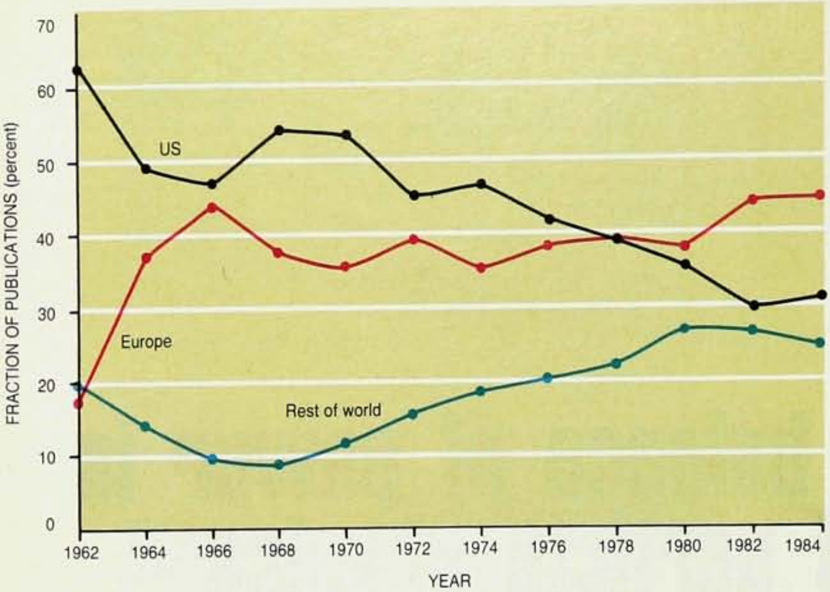



**Share of publications** in experimental high-energy physics, by region and year. Publications are one measure of scientific production. Figure 2

past perfect or dangle in the future conditional while the Europeans pursue the present indicative. Of course, as scientists, we must rejoice in the brilliant achievements of our colleagues overseas. Our concern is that if we forgo the opportunity that SSC offers for the 1990s, the loss will not only be to our science but also to the broader issue of national pride and technological self-confidence. When we were children, America did most things best. So it should again.

Moreover, the argument goes, construction of SSC must begin soon if it is to be completed by the mid-1990s and thus avoid a hiatus between the exploitation of accelerators currently under development and the next generation of facilities. Yet SSC, with its associated detectors and other equipment, will probably cost[2] \$4–6 billion—several times the National Science Foundation's annual budget, which was \$1.6 billion in 1986—and will require the Department of Energy to double its support for the field during the construction period.

In the remainder of this article, we examine how the relative contributions to experimental particle physics of the United States, Western Europe and the rest of the world have changed during the last 25 years. We focus particularly on the early 1980s, combining new publication and citation data with similar statistics for earlier years produced in a study that evaluated[3] the past performance and future prospects of CERN.

## Approach

How can one assess experimental contributions to knowledge in a basic science such as particle physics? The methodology, further details of which can be found[4] elsewhere, has two main elements:

- ▶ Construction of a range of bibliometric indicators of a region's scientific output—number of publications, total number of citations, average number of citations per paper and number of highly cited papers
- ▶ Structured interviews with a wide cross section of researchers to obtain peer evaluations of the scientific outputs of the main accelerators.

The first task involved scanning 11 of the world's leading journals used[3] by particle physicists: *Lettere al Nuovo Cimento*, *Nuclear Physics B*, *Nuovo Cimento*, *Physical Review D*, *Physical Review Letters*, *Physics Letters B*, *Soviet Journal of Nuclear Physics*, *Soviet Physics—Doklady*, *Soviet Physics—JETP* and *JETP Letters*, and *Zeitschrift für Physik C*. This gave us a database of over 10 000 papers presenting new results from elementary-particle-physics experiments at energies above 1 GeV. We also recorded details of the accelerators involved in each experiment. Using the annual editions of the *Science Citation Index* (published by the Institute for Scientific Information, Philadelphia), we noted the number of times each paper had been cited in the year of publication and in subsequent years. Computerizing the publication and citation data enabled us to analyze for each accelerator the following bibliometric indicators of scientific performance:

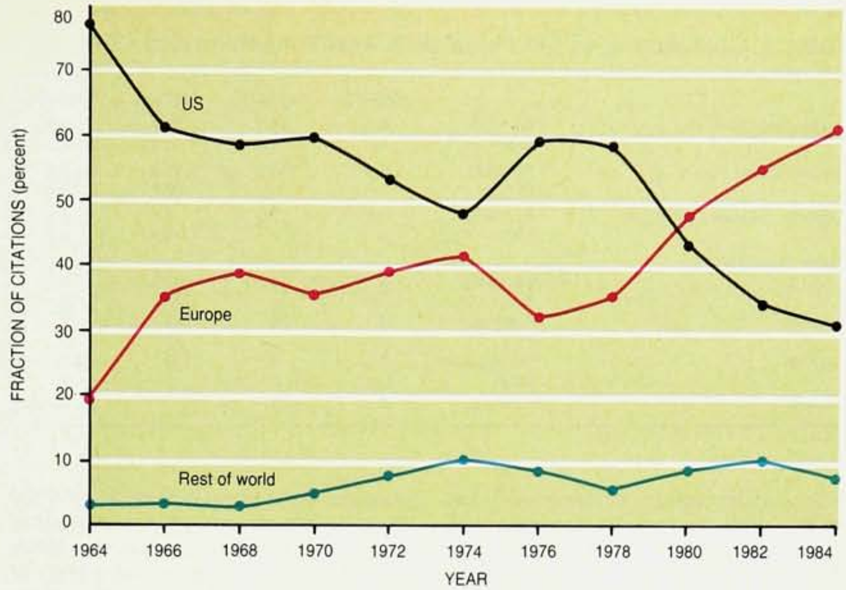
- ▶ Annual publication totals, expressed both in absolute terms and as a percentage of the world total. These totals are a measure of overall scientific *production*.
- ▶ Annual figures on the number of citations to papers published in a given

**Table 1. Comparison of the Brookhaven AGS with the CERN PS**

| | | 1961–64 | 1965–68 | 1969–72 | 1973–76 | 1977–80 | 1981–84 |
|---|---|---|---|---|---|---|---|
| Publication share (%) | | | | | | | |
| | AGS | 8.5 | 19.9 | 17.2 | 10.8 | 5.4 | 3.4 |
| | PS | 20.9 | 28.1 | 24.7 | 21.8 | 17.5 | 5.7 |
| Citation share (%)* | | | | | | | |
| | AGS | 23.1 | 26.8 | 18.2 | 10.1 | 2.9 | 1.8 |
| | PS | 14.2 | 26.1 | 21.9 | 14.7 | 12.7 | 2.1 |
| Average citations per paper* | | | | | | | |
| | AGS | 8.0 | 4.6 | 2.9 | 3.2 | 1.6 | 1.8 |
| | PS | 2.0 | 3.2 | 2.4 | 2.3 | 2.2 | 1.3 |
| Highly cited papers | | | | | | | |
| n≥15 | AGS | 24 | 43 | 22 | 15 | 0 | 1 |
| | PS | 9 | 46 | 19 | 18 | 14 | 1 |
| n≥30 | AGS | 5 | 13 | 1 | 5 | 0 | 0 |
| | PS | 1 | 2 | 1 | 4 | 2 | 0 |
| n≥50 | AGS | 1 | 1 | 0 | 2 | 0 | 0 |
| | PS | 0 | 0 | 0 | 2 | 1 | 0 |
| n≥100 | AGS | 1 | 0 | 0 | 1 | 0 | 0 |

*The figures for citation share and average citations in this and subsequent tables are for the last year in each four-year period.

**Share of citations** to work published in a given year and in the the previous three years, by region and year. Citations reflect the scientific impact of a region's accelerators. Figure 3




year and the previous three years, again expressed both in absolute terms and as a percentage of the world total. These figures are a measure of the overall *impact* on the scientific community of the published work from each accelerator.

▶ Annual figures on the average number of citations per paper. These figures are a measure of the *average scientific impact* of papers from each machine.

▶ Numbers of highly cited papers at various thresholds—for example, those cited 15 or more times in a single year's edition of the *Science Citation Index*. These numbers reveal which accelerators have been responsible for the relatively small number of *major advances* in a field, in contrast with citation totals, which reflect the much larger number of incremental additions to knowledge.

We should stress that these bibliometric statistics are imperfect or "partial" indicators of scientific output—in part they reflect contributions to scientific knowledge and in part they reflect a variety of social, psychological and other factors. Nevertheless, we have found[5] previously that the indicators, when applied to similar research facilities, yield broadly convergent results on comparative scientific performance.

Our second source of information on scientific performance is interviews[6] with 182 particle physicists from a dozen countries. Interviewees were questioned about the main experimental achievements of the world's largest accelerators, and then invited to rank them in terms of:

▶ crucial experiments and discoveries

▶ experiments involving more precise measurements of known particles and properties.

The results revealed a high degree of consistency between the views of different groups of physicists—theorists and experimenters, for example. There was a small "self-ranking effect"—a tendency to evaluate more highly the output of accelerators used by the interviewee—but we overcame this by excluding self-rankings from the results. Overall, the peer rankings of accelerators in terms of crucial discoveries were closely consistent with the data on highly cited papers, while the rankings in terms of precise-measurement experiments were broadly in line with the citation totals.

### Comparing regions

We now turn to the results of the study, focusing first on aggregated data for the three main regions—the United States, Western Europe and the rest of the world (principally Eastern-bloc nations and Japan). We then compare individual US accelerators with their nearest European equivalents, and conclude by briefly examining the future prospects for American experimental high-energy physics.

How have US accelerators, taken as a group, performed relative to accelera-

**Table 2. Comparison of some leading electron accelerators**

| | | 1961–64 | 1965–68 | 1969–72 | 1973–76 | 1977–80 | 1981–84 |
|---|---|---|---|---|---|---|---|
| Publication share (%) | | | | | | | |
| | CEA | 1.2 | 3.5 | 1.6 | 0.3 | — | — |
| | SLAC | — | 1.4 | 7.0 | 6.8 | 4.8 | 2.5 |
| | Cornell | — | — | 1.6 | 1.4 | 1.5 | — |
| | DESY | — | 3.4 | 3.0 | 2.3 | 1.0 | — |
| Citation share (%) | | | | | | | |
| | CEA | 1.3 | 3.9 | 2.0 | 0.2 | — | — |
| | SLAC | — | 1.9 | 12.8 | 6.1 | 5.3 | 2.9 |
| | Cornell | — | — | 1.4 | 1.4 | 1.6 | — |
| | DESY | — | 6.0 | 4.6 | 1.1 | 0.2 | — |
| Average citations per paper | | | | | | | |
| | CEA | 3.0 | 3.9 | 3.4 | 2.1 | — | — |
| | SLAC | — | 4.5 | 5.0 | 3.1 | 3.3 | 4.1 |
| | Cornell | — | — | 2.4 | 3.3 | 3.2 | — |
| | DESY | — | 6.1 | 4.2 | 1.7 | 0.7 | — |
| Highly cited papers | | | | | | | |
| n>15 | CEA | 1 | 7 | 2 | 0 | — | — |
| | SLAC | — | 4 | 21 | 14 | 7 | 3 |
| | Cornell | — | — | 4 | 1 | 5 | — |
| | DESY | — | 10 | 3 | 0 | 0 | — |
| n>30 | SLAC | — | 1 | 4 | 2 | 3 | 1 |
| | Cornell | — | — | 0 | 0 | 2 | — |
| | DESY | — | 1 | 0 | 0 | 0 | — |
| n>50 | SLAC | — | 0 | 2 | 1 | 1 | 0 |
| n>100 | SLAC | — | 0 | 0 | 0 | 1 | 0 |

Dashes indicate accelerators not yet or no longer operating.

## Table 3. Comparison of the Fermilab 500-GeV machine and CERN SPS

| | | 1969–72 | 1973–76 | 1977–80 | 1981–84 |
|---|---|---|---|---|---|
| Publication share (%) | Fermilab | 0.3 | 12.2 | 17.7 | 13.9 |
| | SPS | — | — | 5.1 | 16.3 |
| Citation share (%) | Fermilab | 0.4 | 24.5 | 21.8 | 9.3 |
| | SPS | — | — | 8.7 | 15.3 |
| Average citations per paper | Fermilab | 3.8 | 7.0 | 3.7 | 2.3 |
| | SPS | — | — | 5.1 | 3.3 |
| Highly cited papers | | | | | |
| n>15 | Fermilab | 4 | 71 | 38 | 5 |
| | SPS | — | — | 20 | 12 |
| n>30 | Fermilab | 3 | 26 | 10 | 0 |
| | SPS | — | — | 7 | 2 |
| n>50 | Fermilab | 3 | 9 | 5 | 0 |
| | SPS | — | — | 3 | 1 |
| n>100 | Fermilab | 0 | 0 | 1 | 0 |

tors in other regions of the world? Let us see what the four bibliometric indicators reveal for the period 1961–84. According to the first indicator, of the approximately 360 experimental papers published in the 11 scanned journals in the two-year period 1961–62, 63% reported research on US accelerators, compared with only 17% for West European machines and 20% for the rest of the world. Figure 2 shows how these regional shares varied subsequently. During the 1960s, the US share averaged half as much again as that of Western Europe. From 1970 onward, the gap narrowed, and by 1980 Europe had moved ahead. Over the next four years, European accelerators produced 44% of the world output compared with 30% for US accelerators, a complete reversal of the situation in the 1960s.

Clearly, publications do not all make equal contributions to the advance of knowledge. Let us therefore examine the impact that publications from each region have had on the scientific community. In the period 1961–64, for example, the journals that we scanned published just over 900 experimental papers. In 1964, these were cited nearly 2600 times. However, papers from the three regions had markedly different impacts, with those from US accelerators accounting for a world citation share of 78%, compared with 19% for Western Europe and 3% for the rest of the world. Overall, during the 1960s the US share averaged twice that of Western Europe. As figure 3 reveals, the gap narrowed in the early 1970s but widened again during 1974–78. However, the US's impact has since fallen sharply, so that the picture of scientific performance in 1984 presented by this indicator is a mirror image of that in 1978, with Europe having 62% of the total and the United States 31%.

The number of citations per paper shows similar trends, as figure 4 indicates. In 1964, the 480 US papers published in the period 1961–64 earned 2000 citations—an average of 4.1 citations each, just over twice the corresponding European figure. Although the gap closed in the early 1970s, when the CERN Intersecting Storage Rings came into operation, as with total citations it reopened during the turbulent mid-1970s. Since 1980, however, Western Europe has forged ahead, averaging 4.9 citations per paper in 1984 compared with 3.6 for the US.

Of the four bibliometric indicators, it is the one based on highly cited papers that the majority of scientists would probably regard as the most significant. Figures 5a and 5b show trends in the number of highly cited papers produced by each region. The most pronounced feature in both figures is the sharp peak between 1974 and 1978. During that period, US accelerators were responsible for the great bulk of major advances reported in highly cited papers. However, since then most of the high-impact publications have come out of experiments on European machines. For example, of the 11 papers published in 1983–84 and cited 30 or more times in a year by the end of 1984, only 3 originated in the United States.

In short, figures 2–5 all suggest that US accelerators dominated the field during the 1960s and maintained their supremacy until around 1978, apart perhaps from a brief period in the early 1970s. Since then, Europe has moved ahead, producing more experimental papers, which have been more frequently cited, and apparently accounting for most of the major advances. To understand why such a transformation occurred, it is instructive to examine more disaggregated data on the performance of the main US accelerators relative to their nearest European competitors.

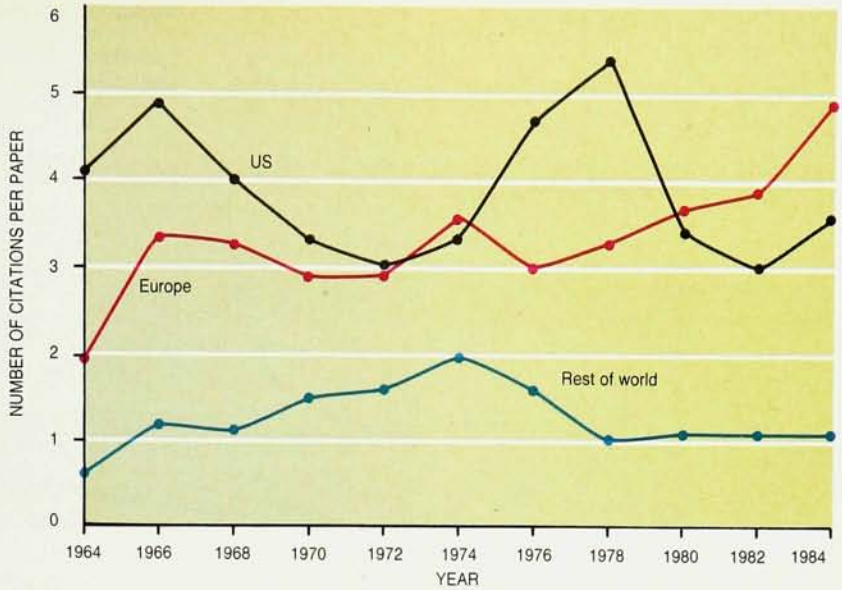
### Individual US accelerators

For much of the 1960s, the world's highest-energy accelerator was the Alternating Gradient Synchrotron at Brookhaven National Laboratory. This machine began operating a few months after the very similar and slightly lower-energy CERN Proton Synchrotron. Table 1 compares the two machines and shows that the AGS produced less than half as many experimental publications as the PS in 1961–64. However, the CERN papers reported data from relatively simple experiments, so their overall impact, as reflected in the number of times they were cited, was less than two-thirds that of the AGS. On average, AGS papers were cited 8.0 times in each year—a typical figure for a new accelerator—compared with 2.0 for the CERN PS, while the divergence in impact was even greater for highly

## Table 4. Comparison of SPEAR at SLAC with DORIS at DESY

| | | 1973–76 | 1977–80 | 1981–84 |
|---|---|---|---|---|
| Publication share (%) | SPEAR | 1.5 | 2.8 | 2.0 |
| | DORIS | 0.5 | 2.2 | 0.9 |
| Citation share (%) | SPEAR | 11.3 | 6.0 | 3.9 |
| | DORIS | 1.2 | 7.7 | 0.9 |
| Average citations per paper | SPEAR | 25.5 | 6.4 | 6.8 |
| | DORIS | 8.2 | 10.3 | 3.6 |
| Highly cited papers | | | | |
| n>15 | SPEAR | 23 | 19 | 6 |
| | DORIS | 3 | 16 | 0 |
| n>30 | SPEAR | 12 | 3 | 2 |
| | DORIS | 2 | 7 | 0 |
| n>50 | SPEAR | 7 | 0 | 0 |
| | DORIS | 1 | 2 | 0 |
| n>100 | SPEAR | 5 | 0 | 0 |

**Citations per paper.** The average number of citations per paper is a measure of the average scientific impact of papers from a region's accelerators. Figure 4




cited papers. Indeed, the three major discoveries that could have been made on either the AGS or PS—the $\Omega^-$, the identification of two types of neutrino, and CP violation—all came from the American machine. It is noteworthy that CP violation, the only particle-physics discovery of the 1960s to win a Nobel Prize, yielded the most highly cited experimental paper of the decade.

Between 1965 and 1968, the gap between the AGS and the PS narrowed. Although the AGS yielded fewer publications than the PS, these were still more highly cited on average, with the result that the total impacts of the two accelerators appear to have been similar in terms of world citation share. For papers cited 15 times in a year, the AGS had by 1968 been overtaken, but it continued to achieve much greater success in generating more important advances.

After 1970, the AGS's publication share fell sharply following difficulties associated with an upgrade of the accelerator. By then, most highly cited papers were being produced not on the AGS or PS (although the latter was responsible for the important discovery[7] of neutral currents in 1973) but on newer machines at SLAC and at Serpukhov in the Soviet Union and on the CERN Intersecting Storage Rings, for which no equivalent facility existed in the United States and which consequently attracted many American users. However, in 1974 it was again the AGS rather than the PS that shared with SLAC the honor of making what was arguably the crucial experimental advance of the 1970s—the discovery of the $J/\psi$ particle, which paved[8] the way for the "new physics." Here again, a Nobel Prize-winning discovery yielded the most highly cited experimental paper of the decade.

How do the bibliometric results discussed above compare with the assessments of particle physicists? Those interviewed ranked the AGS well above the PS in terms of discoveries—they gave the AGS a 9.2 rating on a 10-point scale, compared with 6.9 for the PS. This is in line with its superior record for very highly cited papers. In contrast, for precise-measurement experiments, the interviewed physicists ranked the PS above the AGS—8.5 points versus 7.2—consistent with the data on total citations over the lifetimes of the two machines.

Another important contributor to US success in the 1960s was the SLAC 20-GeV electron linear accelerator. When completed, this was the most powerful machine of its type, and it never had to face the challenge of a direct European equivalent. For several years, the second most powerful electron accelerator was the Cornell 12-GeV synchrotron, while Europe's highest-energy machine was the 7-GeV synchrotron at DESY—the US equivalent of which was the 6-GeV Cambridge Electron Accelerator. What do the bibliometric indicators suggest concerning the relative scientific performance of these electron accelerators?

During the period 1963–65 the Cambridge Electron Accelerator was the world's highest-energy electron accelerator, after which DESY briefly took over that mantle. The bibliometric data in table 2 suggest that CEA users did not fully exploit their lead before the German machine began operating: By 1968, CEA had been responsible for only eight papers cited 15 or more times in a year, while DESY had in its shorter period of operation already produced ten such highly cited papers. However, as the publication and citation shares in table 2 show, both accelerators were rapidly overshadowed by SLAC once that accelerator began experimental work. SLAC was especially successful in producing highly cited papers. Examples include the work on deep inelastic scattering—this provided early experimental evidence of quarks—and on parity violation in inelastic electron scattering. One paper on the latter topic was cited over 100 times in a year. There seems little doubt that SLAC users were extremely successful in exploiting the machine's longstanding advantage as the world's highest-energy electron accelerator. Such a conclusion is in line with the views of 70 high-energy physicists interviewed[9] in another study.

### Fermilab versus SPS

Notwithstanding SLAC's success, the consensus in the late 1960s was that proton machines would continue to make the main experimental contributions to the field. US physicists chose as their principal facility of the 1970s the 500-GeV accelerator that began operating at Fermilab in 1972, four years ahead of the very similar Super Proton Synchrotron at CERN. Table 3 shows that during the period of revolutionary turmoil within the field between 1973 and 1976, Fermilab was well to the fore, earning nearly a quarter of the world citation total and producing over a third of the papers cited 15 or more times in a year. The latter included nine papers with over 50 citations, although four of these—on "trimuons" and the "high-$y$ anomaly"—are now generally considered to have been "mistaken" and to have misled theorists for several years before being corrected by experiments at the CERN SPS.

From the late 1970s on, however, Fermilab's scientific performance declined markedly relative to that of its newer European rival. This was partly because the SPS boasted superior beams and detectors. However, it was

**Highly cited papers. a:** Number of papers cited 15 or more times in a given year. **b:** Number of papers receiving 30 or more citations in a given year. Highly cited papers are one indicator of major advances. Figure 5

also a consequence of budgetary pressures stemming from US policy both at the national level, where the available resources were spread rather thinly among three or four main laboratories, and within Fermilab, where a high proportion of funding was being channeled into an ambitious capital-investment program on the 1-TeV Energy Doubler/Saver and the 2-TeV proton–antiproton collider.

The picture of Fermilab's scientific performance given by the bibliometric indicators is again consistent with the assessments of high-energy physicists. Those interviewed ranked the Fermilab accelerator above the SPS for discoveries—7.2 versus 5.7 on the 10-point scale—as one might expect given the Fermilab machine's greater success in producing highly cited papers. However, the SPS was judged ahead of its American rival for precise-measurement experiments, Fermilab's "mistaken" papers weighing heavily in the minds of many making the assessment.

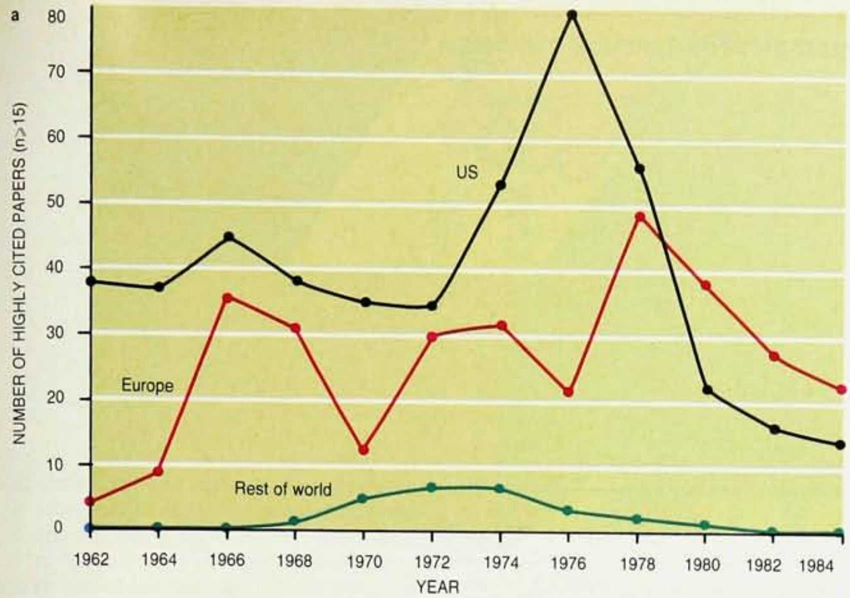
Perhaps the most successful of all US accelerators during the 1960s and 1970s was the electron–positron collider SPEAR. It is ironic that the Department of Energy turned down the proposal to build this novel machine several times, illustrating not only the conservative tendency of the peer-review process but also the growing politicization of decision making in the field, with the small user community at SLAC finding itself a minority among the other laboratories. Consequently, SLAC resorted to the unorthodox procedure of building SPEAR from its operating budget, yet still succeeded in completing the collider a year ahead of DORIS, its German rival at DESY. Given that colliders can conduct only a restricted range of experiments compared with fixed-target accelerators (probably a factor underlying the unpopularity of the SLAC proposal among US experimenters), SPEAR's one-year lead undoubtedly contributed to its greatly superior record compared with DORIS. Although never producing many papers (see table 4), SPEAR earned 11.3% of world citations in 1976, with each paper gaining an average of 25.5 citations—extremely high even for a new facility. Furthermore, no less than five of the eight "crucial" discoveries—those cited 100 times in a year—in the period 1973–76 came from SPEAR. Besides the $J/\psi$, these discoveries included the $\psi'$, the $\tau$ heavy lepton and charmed mesons—altogether a record unmatched by any accelerator in recent times.

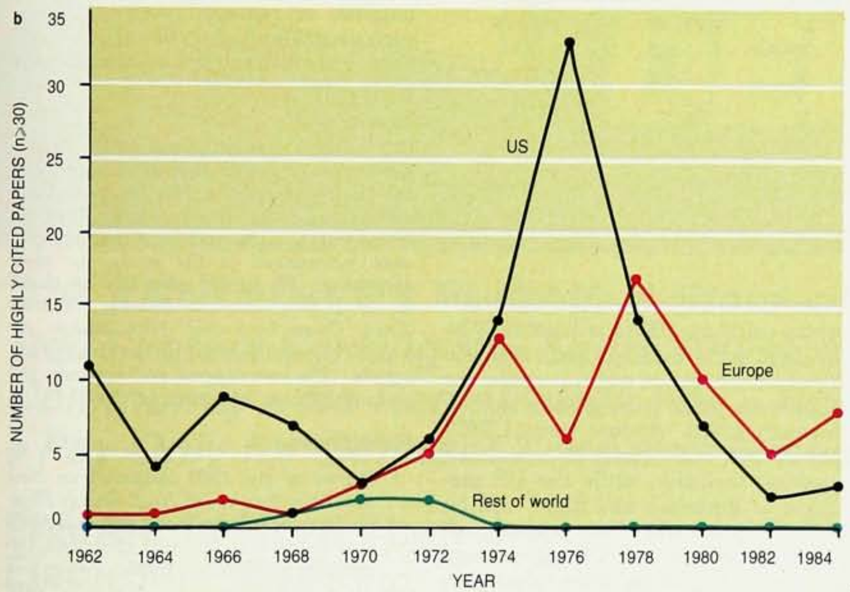
Whereas the AGS, the SLAC electron accelerator, the Fermilab 500-GeV machine and SPEAR each gave US experimenters the world's highest-energy facility of its type, that advantage has since passed to Europe. The turning point came in 1979 with the first publications from PETRA, the large electron–positron collider at DESY. The prompt commissioning of PETRA represented a major technical feat, surprising a US community accustomed to having first access to a new energy range. This time, they had to concede an advantage of over two years to Europe before PEP, the virtually identical facility at SLAC, began experiments, although CESR, a somewhat lower-energy collider, did start operating at Cornell shortly before that. As table 5 shows, PETRA users appear to have been just as successful at exploiting their world lead as Americans had been with earlier accelerators, PETRA experiments having gone far toward establishing the quark–gluon model and quantum chromodynamics theory. Although PETRA yielded only 4.3% of world papers in 1979–80, these papers earned 7.8% of all citations in 1980, with an average of 11.7 citations per paper. During that period, PETRA produced 21 papers cited 15 or more times in a year, nearly as many as SPEAR in its first four years. Even in 1983–84, the citation impact of papers from PETRA was still much greater than that of papers from PEP and CESR. As the US physicist Stanley G. Wojcicki admitted,[10] PETRA users "were able to skim the cream."

Finally, let us consider the machine that has dominated particle physics in recent years—the CERN proton–antiproton collider. Although the idea of using existing accelerators in constructing such a collider was first mooted at CERN and Fermilab at about the same time, for technical and financial reasons CERN was able to start operating its facility in 1981, five years before the first experimental results from the Fermilab $p\bar{p}$ collider. Like other colliders, the CERN machine has not produced many papers (table 6), but it accounted for over 20% of citations in 1984, with an average of 23.9 citations per paper, rivaling SPEAR's peak figure of 25.5 in 1976. Moreover, the CERN machine yielded four papers cited over 100 times in a year, namely those reporting the discoveries of the W and Z particles in 1983. These discoveries, like those of CP violation and the $J/\psi$, have been rewarded with a Nobel Prize. Whether there are similar discoveries waiting to be made in the energy range of the Fermilab collider remains to be seen.

### Future of US particle physics

We have seen how US particle physicists were able to exploit a series of frontier facilities during the first three postwar decades and how in 1979 the




advantage passed to Europe. The output and impact of experiments on US accelerators have, according to all the indicators examined, declined appreciably since then. What then are the prospects for US particle physics? To address this question, we draw upon our analysis of the factors that structured accelerator performance in the past. This analysis is based upon interviews with high-energy physicists.

US high-energy physicists were quick to recognize the shift in the balance of power described above and have warned of the dangers should it continue. One question for policymakers to address, therefore, is whether the trend will continue. In the short term, this seems unlikely, because several new American machines are now coming into operation. The first is the Tevatron Energy Doubler/Saver, which began operating in 1984 at almost twice the maximum energy obtainable on the CERN SPS. However, doubling the beam energy for a fixed-target accelerator represents an increase of less than 50% in center-of-mass energy, giving Fermilab only a comparatively narrow "energy window" to explore what has not already been thoroughly examined elsewhere.

The second new machine is the Fermilab collider, which will study phenomena up to a center-of-mass energy of 2 TeV, over twice the maximum attainable at CERN. According to those interviewed, this advantage should ensure an interesting physics program. Nevertheless, its scientific potential must be seen in the context of that of the CERN collider, which came into operation with an order-of-magnitude increase in energy over the previously largest hadron collider. One might therefore expect the Fermilab machine not to enjoy quite the same success. Even so, the combined facilities at Fermilab will probably enable it to move ahead of CERN before the commissioning of the European Large Electron–Positron collider in 1988 or 1989.

A third factor likely to contribute to a revival of US fortunes is the new Stanford Linear Collider, which should begin operating early in 1987. Although construction of this relatively low-cost facility could probably be justified solely in terms of pioneering an innovative approach to colliding particles—an approach that could pave the way for a new generation of accelerators—the Stanford machine will also, like the Fermilab collider, enjoy a factor-of-two increase in center-of-mass energy over existing machines. Admittedly, users of the SLC will have only two years to exploit the machine's position of world leadership before LEP starts operating at CERN in the same energy range but with the advantage of higher luminosity and more experimental areas. Nevertheless, as we have seen in the past, such a lead has often been decisive for new colliders, so, assuming the problem of low luminosity is overcome, the SLC's prospects seem bright. Overall, therefore, one might expect to see US accelerators playing a more prominent role in coming years. But what of the longer term?

### Questions for the future

Attempting to discuss the future when plans for new facilities are far from settled is not easy, particularly in a fast-moving, unpredictable field such as particle physics. However, our analysis of the factors that have structured

## Table 5. Comparison of the three largest electron–positron colliders

| | | 1979–80 | 1981–82 | 1983–84 |
|---|---|---|---|---|
| Publication share (%) | CESR | — | 2.2 | 3.7 |
| | PEP | — | 1.2 | 4.9 |
| | PETRA | 4.3 | 6.6 | 10.1 |
| Citation share (%) | CESR | — | 1.9 | 5.1 |
| | PEP | — | 0.5 | 6.2 |
| | PETRA | 7.8 | 17.5 | 15.1 |
| Average citations per paper | CESR | — | 5.4 | 6.2 |
| | PEP | — | 2.4 | 7.3 |
| | PETRA | 11.7 | 9.3 | 6.4 |
| Highly cited papers | | | | |
| n>15 | CESR | — | 6 | 3 |
| | PEP | — | 1 | 5 |
| | PETRA | 21 | 12 | 4 |
| n>30 | PEP | — | 0 | 2 |
| | PETRA | 9 | 0 | 0 |
| n>50 | PEP | — | 0 | 2 |
| | PETRA | 2 | 0 | 0 |

## Table 6. Output and impact of the CERN collider

| | 1981–82 | 1983–84 |
|---|---|---|
| Publication share (%) | 1.5 | 4.8 |
| Citation share (%) | 2.2 | 20.7 |
| Average citations per paper | 9.3 | 23.9 |
| Highly cited papers | | |
| n>15 | 7 | 12 |
| n>30 | 4 | 7 |
| n>50 | 0 | 5 |
| n>100 | 0 | 4 |

the performance of accelerators in the past suggests that progress has largely been "technology driven." The successes of the comparatively low-cost but innovative SPEAR electron–positron collider and CERN proton–antiproton collider are examples of this, as is the technical ingenuity shown by SLAC in producing polarized electron beams and thereby making possible the parity-violation experiment mentioned earlier. Such examples lend support to the thesis[11] of the late experimental physicist and historian of science Derek de Solla Price that instrumentational innovation has been a driving force underlying the growth of science. If so, what does this tell us about the longer-term prospects for US high-energy physics?

The early 1990s will probably witness a period of renewed domination by European accelerators, although American researchers will undoubtedly be prominent among their users. By then, CERN is likely to have doubled the energy of LEP, enabling thorough study of the physics of the W and Z particles. If de Solla Price's thesis is correct, however, it is possible that HERA, the electron–proton collider due to be completed at DESY in 1990, will prove the more fruitful machine. Although proposals for new proton or electron accelerators in the past have often included the possibility of subsequently converting them into electron–proton colliders, HERA will actually be the first such facility, and, with no direct competitor in sight, it seems set to produce much new physics during the early 1990s. At that stage, CERN and DESY will again be operating forefront facilities, while the US machines at Fermilab and SLAC will be over five years old. This perhaps explains the efforts that US high-energy physicists are making for a major new facility, SSC, for completion in the mid-1990s.

The SSC project, however, raises awkward questions. The first is the cost. Can the United States, with its budgetary deficit, afford to construct a $4–6 billion facility? And what would the cost be to other scientific fields, many of more direct technological importance?

The second question concerns the present mechanisms for global coordination of new projects in particle physics and "big science" in general. Currently, CERN is proposing placing a Large Hadron Collider similar to SSC, although with only half the energy, in the LEP tunnel (see PHYSICS TODAY, December, page 56). Can either the US or Europe afford such direct competition, or should policymakers now persuade particle physicists to accept a greater degree of interregional collaboration in the construction of new accelerators? Are perhaps the costs of new accelerators so great that particle physicists must finally accept their own rhetoric that this particular field of fundamental intellectual endeavor is a truly international one in which national or regional considerations—such as attempting to wrest "the lead" from some other region—should play no further part?

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