CERN: Past performance and future prospects

I. CERN's position in world high-energy physics

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In a series of three papers, we attempt to evaluate the past scientific performance of the three main particle accelerators at the Geneva-based European Organization for Nuclear Research (CERN) over the period since 1960, and to assess the future prospects for CERN and its users over the next ten to fifteen years.

We concern ourselves in this paper (paper I) with the position of the CERN accelerators in world high-energy physics relative to those at other large laboratories working in the field. We deal primarily with the period from 1969 to 1978, and attempt to establish how the experimental output from the three principal CERN accelerators, *taken as a whole*, compares with that from other major facilities. In undertaking this comparative evaluation, we draw on the method of "converging partial indicators" used in previous studies of three Big Science specialities.

In contrast, the second paper (paper II – Irvine and Martin [12]) focuses in detail on the scientific performance of each of the CERN accelerators *taken individually*. In particular, it asks, first, how the outputs from the CERN 28 GeV (giga or billion electron-volts) Proton Synchrotron compare with those from a very similar 33 GeV American accelerator at Brookhaven National Laboratory over the past two decades. Second, how great have been the experimental achievements of the CERN Intersecting Storage Rings in world terms? And, third, how do the outputs from the CERN 400 GeV Super Proton Synchrotron and from a rival US machine at Fermi National Accelerator Laboratory compare? Attempts are then made to identify the main factors responsible for determining the relative scientific performance of each CERN machine.

These factors are of relevance to the subject of a third paper (paper III – Martin and Irvine [20]) which sets out to assess the future prospects for CERN and in particular for LEP, the large electron–positron collider scheduled for completion in the latter half of the 1980s. What are the construction requirements (financial and technical) associated with LEP, and how easily will they be met? How does the scientific potential of LEP compare with that of other major accelerators under construction around the world? And, in the light of the previous record of the CERN accelerators, to what extent is this potential likely to be realized? The paper concludes with a discussion of the extent to which predictive techniques can be utilized in the formulation of scientific priorities, and of the problems in current science policy-making that such techniques might help address.

1. Introduction

> The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto.

On September 29, 1954, the Convention for the Establishment of a European Organization for Nuclear Research came into operation. This had been signed the year before by the representatives of twelve states. [1] On the same date, the Conseil

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[1] The founding States were Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and Yugoslavia. Austria has since joined, and Yugoslavia withdrawn. In addition, Spain was a member during the 1960s and rejoined in 1983.

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Européen pour la Recherche Nucléaire – a preparatory body set up in 1952 – ceased to exist, although the new organization retained the acronym "CERN." The main purpose of CERN was outlined in Article II of the Convention, and is quoted above.

By 1954, the interim Council had already determined the main components of the future programme for CERN, in particular the construction of a 600 MeV (million electron-volts) synchro-cyclotron, and "a proton synchrotron for energies above ten giga electron-volts" (see e.g. [3, p. 7]). Today, thirty years on, the early estimates made about the future cost and size of the laboratory seem surprisingly modest. In 1952, for example, it was

> estimated that the next stage of development will last seven years and cost a total of 27 million dollars after which the estimated annual running cost of the laboratory would be a maximum of $1\frac{1}{2}$ million dollars [22, p. 1105].

As for the number of staff, it was calculated that "a total staff of about a hundred scientists, draughtsmen and technicians" [23, p. 647] would be sufficient to build the Proton Synchrotron (PS). However, by the end of the initial seven-year development programme in 1960, the total number of CERN staff was well over 1000, and expenditure for that year (the first after the completion of the PS) was also approximately ten times the early estimates – 66 million Swiss francs or about 15 million dollars. CERN continued to grow rapidly, reaching a peak of nearly 3800 employees in 1975. It has since decreased a little in size, so that in 1982 it employed approximately 3600 staff and had an annual budget of over 600 million Swiss francs (MSF) (around 300 million US dollars). As for the new accelerator, LEP, it is estimated that Phase 1 of this project (to reach an energy of 50 GeV in each of two colliding beams) will cost 910 MSF (nearly 450 million US dollars), while the cost of Phase II (to reach 130 GeV) has yet to be publicly specified.

In view of this considerable long-term investment of scientific and financial resources in CERN, it is pertinent to ask how successful the CERN accelerators and the high-energy physicists who use them have proved. As a prominent theoretical high-energy physicist recently remarked in connection with CERN, "the tax-payer is entitled to know what he is getting for his money" (Polkinghorne [30]). But what criteria should be adopted in judging the success of the CERN accelerators and their users? A few years ago, a senior CERN official gave the following explicit definition of the criterion to be used:

> CERN must in the end be judged on whether it has succeeded in its primary mission of enabling particle physics in Europe to be maintained at a world level (Hine [9, p. 181]).

How highly do the scientific outputs associated with the CERN accelerators rank in world terms? At CERN itself, there is little doubt about the answer to this question, as the following quotations make clear.

> The main purpose of CERN is to provide Europe's scientists with first class facilities for high-energy physics research ... The output is measured in new knowledge and in trained people. On these criteria, CERN can stand comparison with any laboratory in the world ... [4, p. 111].

> CERN was conceived to help restore the quality of European science, to provide research facilities beyond the means of individual countries ... In the past twenty-five years, these hopes have been fulfilled beyond the expectations of any of CERN's creators. From accelerators and storage rings, Europe's scientists have contributed greatly to our knowledge of the nature of matter. The CERN laboratory ... puts European high-energy physics on a par with that of any other region of the world [5, p. 227].

But can we go beyond these general statements to establish just how "great" have been the contributions from the CERN accelerators [2] to the advance of scientific knowledge? Where precisely do the CERN experimental contributions [3] rank in relation to those from other accelerator laboratories? It is the purpose of this paper to attempt to answer such questions. We begin with a brief examination of the history of CERN.

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[2] It should be stressed that what is being assessed in this paper and paper II [12] is the scientific performance of the CERN accelerators and of the high-energy physicists who have used them, rather than CERN (the laboratory and its staff) *per se*.

[3] We have not considered here the theoretical outputs from CERN, nor have we examined other types of contribution from the CERN accelerators, such as their training function. For example, the good design and rapid success of the recent proton–antiproton collider experiments (discussed in paper II [12]) clearly owe much to experience with the ISR where physicists took some time to appreciate the importance of 4π-solid angle detectors.

2. The history of CERN and its main accelerators

In 1950, UNESCO instructed its Director-General to encourage the formation of international research centres to increase co-operation in fields where the costs were too great to be borne by most individual countries. High-energy physics (or nuclear physics, as it was still then known) was identified as one such field. While accelerators similar in energy to the 3 GeV Cosmotron and 6 GeV Bevatron, then being built at the Brookhaven and Lawrence Radiation Laboratories in the United States, might just be within the reach of individual nations (and several accelerators of such an energy were eventually built), to go beyond these energies was seen to necessitate international collaboration. This was the principle underlying the multinational collaboration at CERN that over the years was to result in the construction of a series of major particle accelerators.[4]

Initially, work began at CERN in 1952 on plans for the construction of a 10 GeV machine. However, after the design-team had visited Brookhaven, where a similar design-study was in progress, they concluded that, by incorporating the newly invented "strong focusing" concept, it would be possible to built a 30 GeV accelerator for the same cost as the lower-energy "weak focusing" machine originally planned. The interim Council agreed to this change, although with the proviso that the maximum energy be limited to 25 GeV.[5] This was several GeV less than the design-energy of the Brookhaven accelerator, a difference which was subsequently to leave the CERN PS at a significant disadvantage for certain experiments; but otherwise the two designs were very similar. Indeed, although a certain element of competition existed between the CERN and Brookhaven teams during the design and construction period for the two accelerators, a considerable and very fruitful interchange of ideas and technical information also took place (cf. Johnsen [14, pp. 37–39]).

Meanwhile, the design and construction of the smaller 600 MeV synchro-cyclotron went ahead, the first protons being accelerated in 1957. The synchro-cyclotron is still operating over twenty-five years later. During this time, it has supported a wide programme of research, initially in particle physics but increasingly in nuclear physics. However, because such research is no longer classified as "high-energy physics" (which is now normally defined as "physics done with accelerators able to produce primary particles at an energy higher than 1 GeV" – see, for example, Roche [31, p. 3]), and because the costs involved have represented only a small fraction of the CERN annual budget (3 percent in 1977 – see CERN [2, p. 25]), the synchro-cyclotron will not be further considered here.

The Proton Synchrotron (PS) was eventually completed in late 1959, a few months ahead of schedule and – perhaps more importantly from the point of view of CERN's self-confidence – before the rival Brookhaven accelerator. Its maximum energy, at 28 GeV, was also a little higher than the CERN Council had suggested. The PS has been in operation ever since, although it has been subject to a continuous programme of modification and improvement, with the result that its intensity (the number of protons accelerated per pulse) in the latter stages of its lifetime has been 1000 times greater than the original design figure.

Before considering subsequent developments at CERN, it is necessary to examine briefly the structure of experimental high-energy physics in Western Europe at the start of the 1960s. By this time, accelerators of between 1 and 3 GeV were already operating in Britain at Birmingham University, at Saclay and Orsay Laboratories in France, at the Frascati Laboratory in Italy, and at Lund University in Sweden. In addition, various accelerators were under design or construction at Rutherford Laboratory and, a little later, at Daresbury Laboratory in the UK, at DESY, the German laboratory near Hamburg, and at the University of Bonn. V.F. Weisskopf, then Director-General of CERN, clearly saw the need to co-ordinate national and international efforts in Western Europe and to plan for the longer term. Largely at his initiative, an informal committee was set up in 1963 to make recommendations about the future development of high-energy physics in Europe.[6]

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[4] For further details of the early history of CERN, see Goldsmith and Shaw [8]. In addition, a major historical study of CERN is currently being undertaken by a multinational team under the direction of Professor A. Hermann.

[5] According to one of those involved, the Council insisted upon this because of their worry that over-ambition on the part of the design-team might lead them to attempt too demanding a project (Interview, 1981).

[6] This was known as the Amaldi Committee and reported to the CERN Council. For details, see Amaldi [1].

This committee, which subsequently came to assume a more permanent basis as ECFA, the European Committee for Future Accelerators, reported later in 1963. Its two main recommendations were that Europe should build a 300 GeV proton accelerator, and that an intersecting storage rings facility should be added to the Proton Synchrotron at CERN. In addition, the Committee argued that, for "a minimum balanced programme of research in high-energy physics," it was essential that these major European machines be supported by a pyramid of national and regional accelerators of lesser energy. It was envisaged that altogether these would cost up to four times as much as the 300 GeV machine itself (see e.g. Amaldi [1]). Not surprisingly,

> a good many custodians of public funds took fright and thought they were being asked not merely to build the big machine but to provide high-energy physics with a blank cheque [24, p. 1283].

To those nations which had joined CERN in the expectation that the construction of accelerators on an international basis would be cheaper than each country attempting to build its own, the argument that such international facilities in fact required for their full exploitation a very considerable increase in expenditure on national facilities, must have come as something of a surprise. Five years later in 1968, when Britain initially decided against participating in the 300 GeV project, the effects of this report were evidently still being felt, as this commentator's observation makes clear:

> The first attempt to win public support for the big accelerator made quite unrealistic demands that more spending at CERN should be accompanied by more spending domestically, and this gaffe has never been openly repudiated [25, p. 1197].

Despite these question-marks over the wisdom of requesting funding for up to nine additional national and regional accelerators to form the "base of the pyramid programme" (Amaldi [1, p. 1290]), preparations for the two facilities planned to occupy the summit of the pyramid went ahead. The idea of storing protons and causing them to collide head-on in two intersecting rings had been taken up at CERN in 1960, building upon ideas developing by D. Kerst and G. O'Neill in the United States and G. Budker in the Soviet Union. [7] After successful testing of these ideas in 1963 on an electron model (CESAR) built at CERN, the Intersecting Storage Rings (ISR) project was approved by the CERN Council in 1965. One of the evident attractions of the project was its uniqueness – for the first time since the War, Europe was building a major accelerator for which there was no American counterpart. V.F. Weisskopf, Director-General of CERN in the crucial early years of the ISR discussions, lent considerable support to the project because of his

> deep conviction that the physicists of Europe can, and should, be not only on a par with other scientific communities, but ahead at least in some aspects (Weisskopf [35, p. 291]).

Despite the novelty of the machine and the formidable technical problems that it posed, the ISR was completed on schedule – the world's first proton-proton interactions in colliding beams being observed early in 1971. The ISR was in regular operation until the end of 1983, and, like the PS, was considerably modified and improved. In particular, its luminosity (the quantity that, when multiplied by the cross-section in cm^2 for a given process, yields the event rate per second) was increased from an initial value of $10^{28}\ \text{cm}^{-2}\ \text{s}^{-1}$ in 1971 to 4×10^{30} (the design figure) by the end of 1974, and to 1.2×10^{32} by March 1981, an improvement of over four orders of magnitude.

Before going on to discuss the Super Proton Synchrotron, mention should be made of one other important milestone in the history of CERN – the signing in 1967 of an Agreement with the USSR State Committee for the Utilization of Atomic Energy under which a joint scientific and technical programme would be mounted at the 70 GeV proton synchrotron then nearing completion at the Serpukhov Institute of High-Energy Physics. In return for CERN providing technical help and equipment (for example, a rapid beam-extractor) for the Soviet machine, West European physicists were granted access to what was, for a few years, the highest-energy accelerator in the world. [8]. The Agreement was extended in 1975 to allow Soviet teams to participate in experiments at CERN, and again in 1983 to cover new machines at CERN and Serpukhov.

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[7] However, the first idea of using head-on collisions between particles was apparently due to Wideroe in 1943, an idea he subsequently patented in 1953.

[8] An evaluation of the past scientific performance of the Soviet accelerator at Serpukhov is made in Irvine and Martin [11].

The first design for a 300 GeV Super Proton Synchrotron (SPS) was drawn up in 1964, but its construction was not finally authorized until 1971. One factor underlying the delay was the cost of the original design – in 1967, a figure of 1800 MSF (about $420 million at the exchange rates then prevailing) was quoted (Amaldi [1, p. 1290]). This was considerably more than the estimated $240 million cost of an equivalent 200–400 GeV accelerator at Fermi National Accelerator Laboratory, Batavia, Illinois, the design of which was completed in 1967 under the direction of R.R. Wilson. A second reason for the delay was Britain's initial withdrawal from the project in 1968.[9] Since it was intended that Britain contribute nearly one quarter of the cost, this was potentially a severe blow; however, almost immediately CERN was able to propose a revised project costing 25 percent less.

Third, there was profound disagreement among CERN Member States over the site for the accelerator, with several arguing strenuously that it should be built on their soil. Eventually in 1970, a compromise was reached whereby the SPS would be built at Geneva – thus avoiding the political difficulties of agreeing a new site – using the existing Proton Synchrotron as an injector and further reducing the costs to just over 1100 MSF. Moreover, 200 MSF of this total would now be found from reductions in CERN's existing commitments. Hence, only 900 MSF of "new money" would be required, half the cost of the original design and low enough to encourage Britain to rejoin the project. This dramatic reduction of the original cost estimate gave rise to a feeling in the scientific community that CERN

> has often been too presumptuous in its belief that Europe owes high-energy physics a living [26, p. 593]

and that

> if it had not been for the shining example of Dr. R.R. Wilson's bigger but cheaper accelerator at Batavia, Illinois, the chances are that Europe would still be lumbered with a needlessly expensive machine [27, p. 1014].

The SPS proposal was approved in 1971, four years after authorization for the very similar machine at Batavia. This gap was to be maintained, with commissioning of the SPS coming four years after the US accelerator became operational. The effects of this significant lead are discussed in paper II (Irvine and Martin [12]) which considers the relative scientific outputs of these two machines.

The SPS operated continuously until mid-1980 when it was closed for a year to permit construction of an associated proton–antiproton collider. The idea of using the SPS to collide protons and antiprotons had been put forward in 1976 by C. Rubbia, and, following successful tests of the crucial technique of stochastic beam-cooling (developed by S. van der Meer of CERN), the project was approved in 1978. It transpired that the SPS, and in particular its vacuum system, had been so well designed that it could be quickly and relatively cheaply converted into a proton–antiproton storage ring. In contrast, the rival Fermilab machine required extensive structural modifications to add a similar, though higher-energy, storage-ring capability. As a result, it has taken several years longer to convert. The main justification for both these machines was to open up a new energy-region where several phenomena underlying the currently accepted "standard theory" (which unifies electromagnetic and weak interactions) were expected to occur, and in particular to look for the "intermediate vector bosons" believed to be the carriers of the so-called weak force. Because such a discovery would be a major achievement in the history of high-energy physics, there was inevitably a certain element of a "race" between rival laboratories around the world to find these new particles first. This race was "won" by the users of the CERN collider, who early in 1983 announced the discovery of the charged W particle and a few months later the neutral Z particle. These discoveries came after our study had been completed, but they are discussed in paper II.

Finally, brief mention should be made of LEP, although detailed analysis of the prospects for this accelerator are left until paper III (Martin and Irvine [20]). During the 1970s, CERN considered several options for a major new machine for the 1980s and 1990s, and, in the end, after extensive discussions within the European high-energy physics community, settled on the choice of a large electron–positron collider (LEP) capable of producing beams with an energy initially of 50 GeV (Phase I), and eventually of up to 130 GeV. The construction of LEP was authorized at the end of 1981, and the first collisions are planned for 1988.

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[9] For a full analysis of the political and scientific factors underlying this decision, see Gibbons [7].

This concludes our discussion of the main developments in CERN's history. It should be noted that, during this time, the structure of West European high-energy physics has changed considerably. Whereas in 1970, there were some nine national and university accelerators of 1 GeV or more, providing research facilities for perhaps half of Europe's experimental high-energy physicists, now those experimentalists are largely concentrated in just two centres – CERN and DESY (the German facility where international participation has greatly increased with the construction of first DORIS, and then PETRA, two electron–positron colliders [10]).

A similar trend is apparent in the United States: in 1970, besides the three large laboratories at Brookhaven, Fermilab, and Stanford, experimental high-energy physics was also carried out at Argonne, Berkeley, Cambridge, Cornell, and Princeton. Of these latter five, only Cornell is still in the field, with further rationalization a distinct possibility. [11] In view of the growing concentration of Western Europe's high-energy physics effort on the CERN accelerators (nearly three-quarters of the 2000 European experimentalists currently rely on these for their research), it has obviously become an important policy issue to devise adequate methods of assessing the past scientific performance of such facilities, particularly in relation to the main competitor accelerators at the three large United States laboratories.

3. The assessment of scientific performance

How can the performance of experimental high-energy physics facilities be assessed and compared? In considering this question, it should be noted that high-energy physics is funded primarily for scientific reasons – i.e. for the contributions it is judged likely to make to the advance of knowledge. Experimental high-energy physics activity does undoubtedly also lead to significant educational benefits (in the form of highly-trained scientific and engineering personnel), to various types of technological "spin-off" (see Schmied [32]), and, in the case of multinational organizations like CERN, to the fostering of international co-operation. But the primary reason why Member States are prepared to contribute over 600 MSF a year to CERN is because of the promise of important scientific results in coming years. Judgements on the likely future performance of CERN will be based in part on the research potential of programmes on existing and planned accelerators, and also on the "track-record" of scientists in exploiting its facilities to contribute to scientific progress. How can such contributions to scientific progress be reliably assessed?

In a previous study, we developed the method of "converging partial indicators" in which a number of (partial) indicators of scientific progress (publication counts, citations, numbers of highly cited papers or "discoveries," and extensive peer-evaluation) were used to assess matched groups of researchers using similar research facilities in a given field (see Martin and Irvine [19] for details). This method enables assessments to be made of the *productivity* of these facilities and their associted user-groups, the *impact* of the research results, and the *perceived significance* of the research within the scientific community, results which can be combined to give an overall evaluation of their contribution to "scientific progress." It was applied in three different Big Science specialities – radio astronomy, optical astronomy, and electron high-energy physics (see Martin and Irvine [19]; Irvine and Martin [10]; and Martin and Irvine [18]). In each case, a certain convergence between the results based on the various partial indicators was obtained, which permitted conclusions to be drawn as to the relative contributions to scientific progress associated with each of the experimental facilities. The main elements of the method are summarized in table 1. [12]

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[10] See Martin and Irvine [18] for an assessment of the earlier DESY machines.

[11] See, in particular, the report of the recent US Department of Energy Subpanel on Long-Range Planning for High-Energy Physics, chaired by G. Trilling [34].

[12] In view of the comments of scientists critical of the value of citation analysis, it is worth re-emphasizing that citations are used in our method of research evaluation to indicate the "impact" of publications on the advance of knowledge, but not necessarily their "quality" or "importance." Thus a high quality paper in a stagnating field may contribute little to the advance of knowledge in general, and is likely to receive fewer citations than a similar quality paper in a more active field. The "importance" of a paper is defined as the influence it would have were scientific communication completely free from institutional, social and political constraints. For example, a potentially influential paper may go

Table 1
Main problems with the various partial indicators of scientific progress and details of how their effects may be minimized using the method of converging partial indicators

Partial indicator based on	Problem	How effects may be minimized	
A. Publication counts	1. Each publication does not make an equal contribution to scientific knowledge	Use citations to indicate average impact of a research facility's publications, and to identify very highly cited papers	Use only indicators that yield convergent results
	2. Variation of publication rates with specialty, institutional context, etc.	Choose matched research facilities producing similar types of papers within a single specialty	
B. Citation analysis	1. Technical limitations with *Science Citation Index*:		
	(a) first author only listed	Not a problem when dealing with a research facility	
	(b) variations in names (c) authors with identical names (d) clerical errors	Check manually	
	(e) incomplete coverage of journals	Not a serious problem for Big Science	
	2. Variation of citation rate during lifetime of a paper – unrecognized advances on the one hand, and integration of basic ideas on the other 3. Critical citations 4. "Halo-effect" citations	Not a problem if citations regarded as an indicator of impact, rather than quality or importance	
	5. Variations of citation rate with type of paper and specialty	Choose matched research facilities producing similar types of papers within a single specialty	
	6. Self-citation and "in-house" citation (SC and IHC)	Check empirically and adjust results if the incidence of SC or IHC varies between groups	
C. Peer evaluation	1. Perceived implication of results for own research facility and competitors may affect evaluation 2. Individuals evaluate scientific contributions in relation to their own (very different) cognitive and social loctions 3. "Conformist" assessments (e.g. "halo effect") accentuated by lack of knowledge on contributions of different research facilities	1. Use a large representative sample 2. Use verbal rather than written survey in order to press evaluator if a divergence between expressed opinions and actual views is suspected 3. Assure evaluators of confidentiality 4. Check for systematic variations between different groups of evaluators	

In what follows, we apply this method to what have been the three principal CERN facilities over the last two decades – the Proton Synchrotron (PS), the Intersecting Storage Rings (ISR), and the Super Proton Synchrotron (SPS) – comparing them with their main competitors elsewhere in the world, in particular the Brookhaven Alternating Gradient Synchrotron (AGS) on the United States East Coast, the Serpukhov 70 GeV proton synchrotron in the Soviet Union, and the Fermilab 400 GeV proton synchrotron in the American Mid-West. It should be stressed from the outset that our aim is not so much to assess CERN *per se*, but *the scientific output from the CERN accelerators*, irrespective of whether they were used by CERN staff, user-groups from European Member States, or visiting scientists from the United States or Eastern Europe. We are thus comparing the overall contributions to scientific progress made using CERN accelerators with those made using other accelerators. We are *not* assessing the performance of CERN staff (some of whom, for example, were involved in a successful series of experiments at Serpukhov), nor even the performance of West European high-energy physicists – although 80–90 percent of CERN users come from the 13 Member States, some of the major experimental advances (particularly with the ISR) have involved United States groups. It is also important to note the crucial distinction between (1) the overall scientific output from each accelerator, irrespective of the scale of funding and number of users; and (2) their scientific "productivity" or output per unit of input, i.e. their output in relation to funding and numbers of users.

Some comment should also be made concerning the time-period considered in the present study. The first research papers from the CERN PS were published in 1960, with the result that an assessment should, if possible, cover the period from then to the present. This requirement, however, raised a problem for our methodology, since peer-evaluation, which provides perhaps the least problematic of the various partial indicators of scientific progress, only works well for a period of up to ten years or so. There are two reasons for this: memories tend to fade rather quickly outside this time-scale; and, in a scientific field like high-energy physics, many of those involved have only been actively engaged in research for ten years or less.[13]

The approach adopted in our assessment, therefore, is as follows. First, we focus on a recent ten-year period in which peer-evaluation data can be used to complement the full range of other indicators. The period chosen was from 1969 to 1978, partly because this is compatible with that used in an earlier study of electron accelerators (Martin and Irvine [18]), and partly because scientists tend to find it difficult to assess reliably the significance of very recent work. For this period, statistics at a fairly high level of aggregation are used; for example, the three CERN accelerators are treated as one unit. We can then examine the degree of convergence between the quantitative peer-evaluation data and the indicators based on bibliometric (publication and citation) data, the results of which are described in the remainder of this paper. The second time-frame considered covers the 22 years from 1961 to 1982. Given the problem of obtaining systematic peer-evaluation data over such an extended period, we base the assessment largely on the bibliometric indicators interpreted with the aid of qualitative information obtained during interviews with high-energy physicists, together with a much more limited amount of quantitative peer-evaluation data. The data used in this second comparison, which forms the subject matter of paper II, are presented in a more disaggregated form so that each CERN accelerator can be considered separately, and changes over time studied in greater detail. An attempt is then made to interpret the differences in scientific performance of the CERN accelerators relative to their closest competitors, and to identify possible factors explaining those differences.

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unnoticed and uncited if it is written in an obscure or non-English language journal. The "impact" of a publication, in contrast, describes its actual influence on the advance of knowledge, and it is this for which citations provide a (partial) indicator. Note that a "mistaken" paper can sometimes have a significant impact on the advance of knowledge if it stimulates research that might not otherwise have been carried out, and its citation record may reflect this (see Martin and Irvine [19, p. 71] for further discussion).

[13] Twenty-five percent of the 182 researchers interviewed during the study received their Ph. D. in 1970 or later.

4. Inputs to high-energy physics

It is necessary to examine in some detail the various inputs to experimental high-energy physics, in particular the numbers of users for the accelerators, and their respective scales of financial support.[14] This provides the information required below to arrive at judgements on the relative scientific "productivity" (i.e. scientific outputs per unit of input) of different accelerators.

For Western Europe and the United States, we have drawn heavily upon comparative data produced by C. Roche, Head of the Central Planning Office at CERN, and by W. Kirk of the Stanford Linear Accelerator Center (SLAC) in California. Roche has, in turn, used information from censuses conducted by ECFA, the European Committee for Future Accelerators, while Kirk has access to the relevant Department of Energy and National Science Foundation data for the United States. Supplementary information comes from the laboratories themselves – for example, *CERN Annual Reports* give data on numbers of users and annual expenditure in previous years – and this has been used to check the accuracy of the figures. This cross-checking suggests the European and United States figures are accurate to within 10 percent or so.

Data on the approximate numbers of users of accelerators at CERN and DESY in Europe, and at the three principal US laboratories, are shown in table 2 for the years 1970, 1974, and 1978. It is important to note that graduate research students have been included in our figures. This has not always been the case in previous studies of the size of the high-energy physics community, particularly in the United States, with the result that some of the previously quoted figures have been rather smaller.[15] We have then attempted to estimate the total number of high-energy physics experimentalists in the world, in order to calculate the approximate percentage of active researchers using the accelerators at each of the five largest Western laboratories. The figures reveal that, for CERN, the figure has risen from just under 20 percent in 1970 to approximately 30 percent in the second half of the 1970s, as smaller national accelerators were closed or diversified from high-energy physics to nuclear physics and synchrotron-radiation research. It should be noted, however, that the CERN figure for 1970 does not include the 100 or more European physicists preparing experiments to be run on the ISR in later years – these are part of the figure of 1000 quoted for "other" West European experimentalists. In the same way, the 1974 figure of 550 "others" in Western Europe includes some in the early stages of planning experiments for the CERN SPS. Similar considerations apply to our data on the users of accelerators at the other laboratories.[16] Despite these qualifications, it can nevertheless be seen that during the 1970s the CERN accelerators have catered for a far larger number of physicists than Fermilab (used by 11–12 percent of world experimentalists), Brookhaven and SLAC (both approximately 5–6 percent), or DESY (whose percentage share has risen from 3 percent to over 6 percent, as first DORIS and then PETRA, the two electron–positron storage rings, came into operation).

The production of reliable data on which to base international comparisons of funding is even more difficult. There are several major problems here. First, the figures must be fully comparable – that is, they must be based on common categories and definitions. In view of the importance of such figures in evaluations of a centre's relative cost-effectiveness, this has, in the past, given rise to some debate between C. Roche at CERN and W. Kirk at SLAC. They have, however, now succeeded in reaching approximate agreement on the criteria to be used in such comparisons, and, as far as possible, we have adopted their categories. Second, one must allow for the varying inflation rates in different countries. Third, fluctuations in exchange rates

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[14] In previous papers, we have considered other inputs, such as numbers of technical support staff, as well as attempting to separate capital costs from recurrent expenditure. However, this gives little additional information, and we assume here that numbers of users and overall funding levels (capital and recurrent) are sufficient to define the relative scale of research activity at each accelerator (with certain provisos discussed later).

[15] For example, see Moravcsik [21], p. 84]. We include graduate research students in these comparisons since they form an integral part of most experimental high-energy physics teams, for example often undertaking complex data-processing tasks.

[16] In addition, the figure shown in table 2 for SLAC in 1978 is smaller than that quoted in Martin and Irvine [18, table 1] because the latter included a large number of experimentalists preparing to carry out future experiments on the new electron–positron collider, PEP.

Table 2
Numbers of experimental high-energy physicists (HEPs) [a]

		1970	1974	1978
W. European HEPs	CERN users	850 (18%)	1250 (28%)	1400 (32%)
	DESY users	150 (3%)	200 (4.5%)	280 (6.5%)
	Others [b]	1000 (21%)	550 (12%)	320 (7.5%)
	Total W. Europe	2000 (43%)	2000 (44%)	2000 (45%)
US HEPs	Brookhaven users	300 (6.5%)	~ 250? [d] (5.5%)	200 (4.5%)
	Fermilab users	–	~ 450? [d] (11%)	550 (12%)
	SLAC users	200 (4.5%)	300 (6.5%)	250 (5.5%)
	Others [b]	1000 (21%)	~ 300? (5.5%)	200 (4.5%)
	Total US	1500 (32%)	1300 (29%)	1200 (27%)
HEPs in rest of world (E. Europe, Japan, etc.) – estimate [c]		700–1700?	700–1700?	700–1700?
Estimated world total		4700(±500) (100%)	4500(±500) (100%)	4400(±500) (100%)

[a] These include Ph. D. students carrying out research work. As with funding, these are approximate figures only. The data for 1978 are probably the most accurate, the European figures having been taken from Roche [31, p. 5]. Other data came from annual reports (e.g. CERN [3, p. 17], internal documents provided to us by the various laboratories, and Kirk [15, fig. 5].

[b] These include the users of various smaller accelerators and of accelerators overseas, as well as a number of physicists in the very early stages of planning new experiments or analyzing experimental data obtained in previous years.

[c] These are very approximate estimates only. It is assumed that the effect of the decreasing number of Soviet accelerators used for high-energy physics has been largely compensated for by the growth of the subject in other countries such as Japan.

[d] Estimates only.

must also be taken into account. Lastly, there is the problem that official exchange rates do not necessarily reflect actual purchasing power in different countries. To overcome these second and third problems, we have used the two specialized inflation indices (based on changes in the cost of scientific equipment, salaries, etc.) produced by CERN and SLAC [17] to convert all expenditure figures to 1978 prices (in Swiss francs for Europe, and dollars for the US). Then, to overcome the fourth problem, the Stanford Research Institute "competitive value index" – i.e. the exchange rate corrected for the real purchasing power of the dollar in the United States – has been used to convert all the US figures (in 1978 prices) to Swiss francs. For 1978, the "competitive value index" was \$1 = 2.7 Swiss francs, an exchange rate that both Roche [31, p. 4] and Kirk [15, The Richter Method] take to be realistic to within 10 percent or so.

Table 3 gives the estimated figures for overall European and US government spending on high-energy physics in both actual prices and equivalent 1978 prices, while in table 4 the US figures have been converted from 1978 dollars to 1978 Swiss francs. Table 4 also contains a very approximate estimate of total world expenditure on high-energy physics, which has been used to convert the figures for the major West European and US facilities into percentage shares of total expenditure. These figures suggest that, in the case of CERN, this percentage has grown from 15 percent in 1970 to some 25 percent in the second half of the 1970s. In addition, a large fraction of the "other" West

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[17] It has been assumed that the SLAC inflation index is appropriate for the other American laboratories and that the CERN index is not too dissimilar to that for DESY.

Table 3
European and US funding for high-energy physics (HEP) [a]

		1966 [b]		1970 [b]		1974 [b]		1978 [b]
		1966 prices	(1978 prices) [c]	1970 prices	(1978 prices) [c]	1974 prices	(1978 prices) [c]	1978 prices
W. European funding in millions of Swiss francs (MSF)	CERN [d]	165	(270)	302	(440)	580	(670)	565
	DESY	50	(80)	70	(100)	100	(115)	115
	Other	335	(550)	430	(620)	480	(555)	375
	Total W. Europe	550	(900)	802	(1160)	1160	(1340)	1055
US funding [e] in millions of dollars ($M)	Brookhaven	26	(57)	32	(59)	33	(48)	42
	Fermilab	–	(–)	56	(102)	65	(94)	84
	SLAC	29	(64)	27	(49)	26	(38)	87
	Other	109	(240)	117	(215)	63	(91)	90
	Total US	164	(361)	232	(425)	187	(271)	303

[a] These are the estimated figures for total expenditure on high-energy physics (i.e. capital and construction costs as well as recurrent expenditure).

[b] The figures are for calendar years in W. Europe, and for fiscal years in the US.

[c] Inflation indices calculated by C. Roche (at CERN) and W. Kirk (at SLAC) have been used (see Kirk [15, fig. 3]. The conversion factors for changing the 1966 figures into equivalent 1978 prices are 1.64 (W. Europe) and 2.20 (US); for 1970, 1.45 and 1.83; and for 1974, 1.15 and 1.45.

[d] These are the figures for the contributions from Member States to CERN (i.e. they exclude bank interest, miscellaneous income, etc.). In addition, an allowance for non-HEP programmes at CERN has been made by subtracting a figure of between 5 percent (in 1966) and 3½ percent (in 1978).

[e] These figures are based on (1) data provided by the US Department of Energy (DoE) which show DoE support of $148 M in 1966, $215 M in 1970, $169 M in 1974, and $280 M in 1978; and (2) data quoted in Kirk [15, fig. 3] showing National Science Foundation support of $16 M, $17 M, $18 M and $23 M in 1966, 1970, 1974 and 1978 respectively.

Table 4
World funding for high-energy physics (1978 Swiss francs)

		1966 MSF [a]	1970 MSF	1974 MSF	1978 MSF
W. European funding	CERN	270 (10%)	440 (15%)	670 (26%)	565 (24%)
	DESY	80 (3%)	100 (3.5%)	115 (4.5%)	115 (5%)
	Other	550 (22%)	620 (21%)	555 (21%)	375 (16%)
	Total W. Europe	900 (35%)	1160 (39%)	1340 (52%)	1055 (44%)
US funding [b]	Brookhaven	145 (5.5%)	160 (5.5%)	130 (5%)	115 (5%)
	Fermilab	–	275 (9%)	255 (10%)	225 (9.5%)
	SLAC	175 (6.5%)	135 (4.5%)	100 (4%)	235 (10%)
	Other	650 (25%)	580 (19%)	245 (9.5%)	245 (10%)
	Total US	970 (37%)	1150 (38%)	730 (28%)	820 (34%)
Estimated funding [c] – rest of world (E. Europe, Japan, etc.)		~ 500–1000?	~ 500–900?	~ 400–700?	~ 400–700?
Estimated world total (billions of Swiss francs)		2.6 BSF (±0.3) (100%)	3.0 BSF (±0.2) (100%)	2.6 BSF (±0.2) (100%)	2.4 BSF (±0.2) (100%)

[a] Millions of Swiss francs.

[b] A conversion rate of 1$ = 2.7 SF in 1978 has been used. This is based not on the official exchange rate, but on the Stanford Research Institute "Competitive Value Index" by which exchange rates are corrected for real purchasing power in different countries (see Kirk [15]; Roche [31, p. 4]).

[c] These are very approximate estimates only. In deriving them, it has been assumed that countries outside Western Europe and the United States spend somewhere between 50 and 100 percent of the amount budgeted by the United States. In 1966, when the Soviet Union was constructing the large accelerator at Serpukhov, the figure is likely to have been in the upper part of this range, while in 1970 (when the US was in the midst of building the Fermilab accelerator) it is more likely to have been in the lower part.

European funds is spent on supporting university groups using the CERN accelerators, a fraction that has undoubtedly been increasing during the 1970s as national accelerators were closed and the percentage of European experimentalists using CERN rose from less than 45 percent in 1970 to 70 percent in 1978. This change in the structure of funding can be taken into account by allocating the "other" funds in the ratio of CERN users to other European experimentalists (including DESY users), having first subtracted a small amount to cover the cost of the few remaining national facilities. The result is that in 1978, for example, the CERN share of world expenditure is raised from 24 percent to over 30 percent, bringing it closely into line with the figure in table 2 on CERN users as a percentage of the world total of experimentalists. (In 1978, CERN accelerators catered for 32 percent of all experimentalists.)

Similarly, the US "other" funds were utilized partly to support university users of Brookhaven, Fermilab, and SLAC, and partly to operate the Argonne and Cornell accelerators in 1978, and the Berkeley, Cambridge and Princeton accelerators in earlier years. Thus, apportioning part of the US other costs to the three national laboratories raises the shares of world expenditure of Fermilab to 12–13 percent, Brookhaven to 6–7 percent, and SLAC to about 6 percent (except in 1978, when it was much higher because of the construction of PEP), figures again very close to the user-percentages given in table 2.

The results of integrating these "other" expenditures for both Europe and the United States in the way described are shown in table 5, alongside figures for the distribution of world experimentalists over the ten-year period 1969–78. The close similarity of these figures for all five centres suggests that the cost per experimental high-energy physicist does not differ greatly between centres (cf. Roche [31, table 1 and p. 6]). This is provided that (a) one corrects official exchange rates for real purchasing power; and (b) it is recognized that the total expenditure in a given year may be untypical because of a large capital-construction element. Thus, the figures in table 6 on the approximate cost per high-energy experimentalist seem to show higher costs for America in 1970 and 1978, and for Europe in 1974. Yet these apparent differences are very largely due to the fact that the US figure for 1970 contained a significant element for the construction of Fermilab, and that for 1978 included the construction costs of PEP and CESR, the Cornell Electron Storage Ring, while the European figure for 1974 was swollen by the construction costs of the SPS. With these reservations, the figures in table 5 can be regarded as giving a reasonable indication of the scale of inputs to the CERN accelerators relative to those for other major facilities.

Table 5
Inputs for major accelerators at the five main Western high-energy physics centres, 1969–78

	Users (% of world total)	All-inclusive funding (% of world total)
CERN	~ 25–32 [a]	~ 25–32 [a]
DESY	~ 4 [b]	~ 4–5 [b]
Brookhaven	~ 5–6	~ 6–7
Fermilab	~ 11–12 [a]	~ 12–13
SLAC	~ 5–6	~ 6 [b]

[a] Except in the very early years of the decade, 1969–78.
[b] Except in the last year or so of the decade.

Table 6
Approximate cost per experimental high-energy physicist [a] (in 1978 Swiss francs)

	1970 MSF	1974 MSF	1978 MSF
W. Europe	0.58	0.67	0.53
United States	0.77	0.56	0.68

[a] These data were obtained by dividing overall funding for high-energy physics (adjusted to 1978 prices – see table 4) by the number of experimentalists. This procedure ignores the fact that some funds are used to support theoretical work. However, such research is relatively cheap compared with experimental work (at CERN in 1977, for example, it accounted for only 1½ percent of the total budget – see [2, p. 25]) so the effect of this approximation should not be too great.

5. Accelerator outputs – scientific publications

While publication counts in themselves constitute a rather problematic indicator of scientific progress, they nevertheless provide some useful information and are a necessary complement to the other partial indicators used in this study. The first step in producing these figures was to compile as comprehensive a list as possible of all experimental high-energy physics papers published over the period 1961–82. This was done by scanning fully the 11 principal international journals [18] used by particle physicists, noting details of all papers which would generally be regarded as coming under the category of "experimental high-energy physics". [19] Each paper was then read to establish which accelerator (or accelerators [20]) had been used to produce the experimental data reported. It should be noted that, under this procedure, preprints and conference papers were excluded from consideration on the grounds that nearly all such articles are eventually published in a scientific journal, and to have included them would have introduced an element of "double-counting". [21]

The list thus derived was then cross-checked against various data compilations (especially Particle Data Group [28]) and annual publication lists provided by the main centres. [22] This increased the total number of publications by about 5 percent. Some of these additional papers involved borderline definitions as to whether the results reported were "experimental," or indeed whether they should be treated as "high-energy physics" – if there was any doubt, they were included. The remaining additional papers were published in journals other than the 11 scanned, mainly in general physics, or "national" high-energy physics, journals. Cross-checking in this way suggested that our final publication list was 90–95 percent complete in its coverage of papers from Western accelerators, but rather less in the case of Soviet and Japanese accelerators. This should be borne in mind when considering the figures in table 7, and subsequent tables relating to Soviet and Japanese accelerators. [23]

Table 7 presents the resultant data, giving a breakdown of world experimental high-energy physics publication output over the period 1969–80. [24] As can be seen, approximately 500 papers were published each year during this period (i.e. 1000 every two years). Of these, the three CERN accelerators were responsible for 26.5 percent (see the final column of the table). This is well over twice as many as the Brookhaven AGS accelerator (11.5 percent), three times the Fermilab figure (8.5 percent), nearly three-and-a-half times that of SLAC (8 percent), and some eight times the DESY figure (3 percent).

The next stage of our method of "converging partial indicators" is to evaluate the relative scientific productivity (i.e. output per unit of input) of the accelerators, and for this the figures on publication counts need to be set against those for inputs. The results of this analysis are shown in table 8. It can be seen that in the case of the CERN accelerators, their percentage of the total world output of experimental papers (26.5 percent) is very similar to their share of world resources (between a quarter and a third). The situation is similar for the DESY accelerators, whose share of world resources, though increasing from about 3 percent to 6 percent over the decade 1969–78 (see tables 2 and 4), has been matched by an equivalent growth in their share of the world's papers. The Brookhaven accelerator, in contrast, appears to have achieved a rather higher level of productivity – 11.5 percent of all publications compared with some 5–7 percent of funds and users. However, many of the papers that appeared in the early part of this decade were based on experiments carried out before 1969, so this comparison may in some respects be slightly misleading. Qualification is also needed in the case of Fermilab, for which, given its comparatively late entry into the field, the period 1973–78 provides the fairest indication of its productivity. In this period, its share of publication output (13.5 percent) is similar to its share of funds and users (11–13 percent). Finally, we can note that the

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[18] See note c to table 7.

[19] See notes a and b to table 7 for the definitions used.

[20] See note e to table 7.

[21] Citations to preprints were, however, included in the citation analysis – see the next section for details of the way in which they were treated.

[22] In our previous work on electron high-energy physics (Martin and Irvine [18]), we relied primarily on publication lists provided by the research centres to derive data on numbers of publications. However, it has since become evident that the completeness of these lists varies across centres, largely because of the different procedures used by visiting scientists to report papers published in subsequent years after carrying out experiments. Their comprehensiveness also varies over time: the lists used for SLAC, and to a lesser extent DESY, for example, were found to be somewhat incomplete for the late 1960s and early 1970s.

[23] For further discussion of the problems of comparing the outputs of Soviet and Western accelerators, see Irvine and Martin [11].

[24] Although this paper is concerned primarily with the ten-year period from 1969 to 1978, some of the work carried out towards the end of this time was not published until 1979 or 1980. Figures for 1979–80 are therefore included.

Table 7
Numbers of experimental high-energy physics[a] papers[b] published in international journals[c] during the preceding two years

		1970	1972	1974	1976	1978	1980	Total 1969–78
Papers from W. European accelerators[e]	CERN	235[d] (25%)	275 (27%)	265 (23.5%)	335 (28.5)	320 (29%)	235 25.5%)	1435 (26.5%)
	DESY	25 (2.5%)	35 (3.5%)	35 (3%)	30 (2.5%)	45 (4%)	60 (6.5%)	175 (3%)
	Others ·	80 (8.5%)	90 (9%)	105 (9%)	80 (6.5%)	65 (5.5%)	55 (6.5%)	420 (7.5%)
	Total W. Europe	340 (36%)	400 (39.5%)	410 (35.5%)	445 (38%)	435 (38.5%)	350 (38%)	2025 (37.5%)
Papers from US accelerators[e]	Brookhaven	180 (19%)	150 (14.5%)	155 (13.5%)	95 (8%)	60 (5.5%)	50 (5.5%)	635 (11.5%)
	Fermilab	–	5 (0.5%)	105 (9%)	175 (15%)	180 (16.5%)	180 19%)	470 8.5%)
	SLAC	55 (5.5%)	80 (8%)	80 (7%)	110 (9.5%)	105 (9.5%)	55 (6%)	425 (8%)
	Others	255 (27%)	210 (20.5%)	180 (15.5%)	105 (9%)	90 (8%)	45 (5%)	840 (15.5%)
	Total US	490 (51.5%)	445 (43.5%)	515 (45%)	485 (41%)	435 (39%)	330 (35.5%)	2370 (44%)
Papers from other accelerators[e] (Soviet Union, Japan)		120 (12.5%)	175 (17%)	225 (19.5%)	245 (21%)	250 (22.5%)	250 (27%)	1010 (18.5%)
World total		945 (100%)	1020 (100%)	1150 (100%)	1180 (100%)	1115 (100%)	930 (100%)	5410 (100%)

[a] High-energy physics is defined as "physics done with accelerators able to produce primary particles at an energy higher than 1 GeV" (Roche [31, p. 3]).

[b] We have attempted to use the same definition of an "experimental" high-energy physics paper as the international Particle Data Group – that is, the paper must "contain new (i.e. previously unpublished) experimental data .... If it is uncertain whether data is new, it is treated as new .... We exclude theoretical papers, unless a new particle or reaction property is derived from an analysis (of data) which is not based upon any particular phenomenological model .... Other subjects excluded are instrumentation, nuclear level structure, and studies of cosmic rays...." (see Particle Data Group [28, p. 1.2]). However, unlike the Particle Data Group, we have excluded "reviews or compilations of data ..., preprints, book articles, conference proceedings, theses [and] experiment proposals" [28, p. 12].

[c] This publication list was derived by scanning the following 11 journals: *Lettere al Nuovo Cimento; Nuclear Physics B* (and before that, *Nuclear Physics); Nuovo Cimento; Physical Review D* (and before that, *Physical Review); Physical Review Letters; Physics Letters B* (and before that, *Physics Letters); Soviet Journal of Nuclear Physics; Soviet Physics – Doklady; Soviet Physics – JETP* and *JETP Letters*; and *Zeitschrift für Physik C.* Additional information came from annual reports and publication lists produced by the various laboratories, and data compilations such as Particle Data Group [28] so the final publication list contains a small number of papers published in a variety of other journals.

[d] All totals have been rounded to the nearest 5, and all percentages to the nearest 0.5 percent.

[e] All the papers were scanned to establish which accelerator was used to obtain the experimental results. In a small number of cases (2.4 percent), more than one accelerator was used. For such cases, each accelerator used was credited with that paper, with the result that there is a small element of "double-counting" in the publication totals.

SLAC machines appear to have achieved a relatively high scientific productivity – 8.0 percent of all papers compared with 5–6 percent of funds and users.

However, as we have stressed earlier (see table 1), analyses based on publication counts alone can be misleading, since the publications from one accelerator may on average have had considerably more impact on the advance of knowledge than those from another. The next step, therefore, is to examine the relative overall impacts of those publications.

Table 8
Relative scientific productivity of major accelerators, 1969–78: Experimental publications in relation to inputs

	Inputs [a] (% of world total)	Experimental publications (% of world total)
CERN	~ 25–32 [b]	26.5
DESY	~ 4–5 [c]	3
Brookhaven	~ 5–7	11.5
Fermilab	~ 11–13 [b]	8.5 (13.5) [d]
SLAC	~ 5–6 [c]	8

[a] These figures have been taken from table 5, and represent an average of the figures for numbers of users and for funding.
[b] Except in the very early years of the decade, 1969–78.
[c] Except in the last year or so of the decade.
[d] Average figure for the period 1973–78.

6. Accelerator outputs – overall impact of scientific publications

Analysis of the relative frequency with which papers from one accelerator (or set of accelerators) are subsequently cited by scientists in other articles may be used to provide various indicators of their impact on the advance of scientific knowledge, though, as with other indicators, these are by no means unproblematic. [25] Three citation indicators – total numbers of citations, citations per unit input, and citations per paper – are of relevance here in assessing general scientific impact, while a fourth – numbers of highly cited papers – is used in the next section to evaluate more specifically which accelerators were responsible for the main breakthroughs in high-energy physics between 1969 and 1978.

The data-base from which all four citation indicators were constructed was compiled by manually scanning the *Science Citation Index* [33] for the years 1961–82. Using this method, full and relatively accurate citation records were obtained for the experimental publications from each accelerator. Manual scanning largely overcomes the technical problems of citation analysis listed in table 1 (mis-spelt names, incorrect volume or page numbers, etc.). And since the *Science Citation Index* covers the 11 main international high-energy physics journals, as well as most of the others occasionally used by experimentalists, the citation counts should (as was the case with the publication totals) be around 90–95 percent complete (again with the exception of the Soviet and East European figures [26]).

One special problem affecting citation analysis in high-energy physics should perhaps be mentioned. This is the extensive use of references to a preprint until the paper concerned is published. [27] (This practice ends virtually as soon as the paper is published, so it normally affects only the citations to a paper during its first year.) Such citations have all been credited to the paper that supersedes the preprint, and the same procedure has been adopted for references to articles "in press" and "to be published."

Comparative data on the overall level of citations gained by papers from the accelerators at each of the main Western high-energy physics centres are provided in table 9. Figures are given for even years only, and refer to the total numbers of citations made in those years to experimental journal articles published during the preceding four years, [28] i.e. the 1972 figures are for the number of citations in the 1972 edition of the *Science Citation Index* [29] to all papers published between 1969 and 1972. It can be seen that papers reporting results produced on CERN accelerators

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[25] For a discussion of the intrinsic problems in citation analysis, see Martin and Irvine [19].

[26] See note a to table 9 and the discussion of this problem in Irvine and Martin [11].

[27] This problem is particularly pronounced for East European publications in which there is a far greater incidence of references to preprints than to published articles. This mode of referencing arises largely because of the frequently long delays before papers are published, but also because some East European research groups do not have easy access to journals and instead rely on informally circulated preprints. The Soviet citation totals must therefore be treated with *great caution* since they may represent an appreciable underestimate of the "true" citation totals (see Irvine and Martin [11]).

[28] Since most experimental high-energy physics papers have a peak citation-rate one to two years after publication, the use of a period longer than four years does not significantly affect the overall citation distribution, though it does tend to mask changes over time.

[29] While most of the citing articles in, say, the 1972 edition of the *Science Citation Index* will have been officially published in 1972, a few will be dated 1971 even though they actually appeared in 1972, too late for inclusion in the 1971 edition. Similarly, the 1973 edition will contain a few citing articles dated 1972. We have assumed that these two effects approximately cancel out when dealing with large numbers of publications.

Table 9
Numbers of citations [a] to experimental journal articles published during the preceding four years

		1972	1974	1976	1978	1980	Total 1972 + 1974 + 1976 + 1978
Citations to papers from W. European accelerators	CERN	1420 [b] (27%)	2150 (31.5%)	1840 (24%)	2080 (25.5%)	1740 (28.5%)	7490 (26.5%)
	DESY	250 (4.5%)	180 (2.5%)	180 (2.5%)	450 (5.5%)	950 (15.5%)	1060 (4%)
	Others	420 (8%)	520 (7.5%)	440 (5.5%)	290 (3.5%)	240 (4%)	1680 (6%)
	Total W. Europe	2090 (39.5%)	2850 (42%)	2460 (32%)	2830 (34.5%)	2920 (48%)	10,230 (36.5%)
Citations to papers from US accelerators	Brookhaven	960 (18%)	760 (11%)	780 (10%)	420 (5%)	170 (3%)	2910 (10.5%)
	Fermilab	20 (0.5%)	780 (11.5%)	1900 (25%)	2620 (32%)	1320 (21.5%)	5320 (19%)
	SLAC	670 (12.5%)	670 (10%)	1330 (17%)	1250 (15%)	690 (11.5%)	3920 (14%)
	Others	1150 (21.5%)	990 (14.5%)	570 (7.5%)	570 (7%)	430 (7%)	3280 (11.5%)
	Total US	2800 (53%)	3190 (47%)	4590 (59.5%)	4850 59.5%)	2620 (43%)	15,430 (55%)
Citations to papers from other accelerators (Soviet Union, Japan)		420 (8%)	740 (11%)	690 (9%)	510 (6%)	550 (9%)	2350 (8.5%)
World total		5310 (100%)	6780 (100%)	7740 (100%)	8190 (100%)	6090 (100%)	28,020 (100%)

[a] These figures have been derived using the *Science Citation Index*. This scans all 11 of the main international journals used in drawing up the publication list, as well as several of the other journals containing the occasional high-energy physics paper. Therefore, like the publication totals, the citation totals should be 90–95 percent complete, except in the case of papers from Soviet and Japanese accelerators. (Some Soviet papers are published in the physics journals of the various Soviet Republics, and these are not scanned by the *Science Citation Index*.)

[b] All totals have been rounded to the nearest 10, and all percentages to the nearest 0.5 percent.

earned 26.5 percent of all world experimental high-energy physics citations for the period 1969–78.[30] This is almost one-and-a-half times that of Fermilab's share (19 percent), twice the SLAC share (14 percent), two-and-a-half times Brookhaven's share (10.5 percent), and seven times that of DESY (4 percent). Thus, in terms of absolute numbers of citations, it would appear that the *total* impact of work carried out on CERN accelerators has been greater than that from any other laboratory over this period. Further comment will, however, be made on this question once the data on the distribution of highly cited papers have been taken into consideration.

It is important to recognize that variations in the total numbers of citations gained by the accelerators at different centres may reflect differences in activity levels as much as the relative significance of their respective experimental outputs. (We should remember, in particular, that comparison is being made between the outputs of one accelerator at Brookhaven and Fermilab, and those of three at CERN.) It is essential, therefore, to relate these citation totals to the inputs for the various accelerators. The relevant figures are given in table 10 and suggest that, in terms of citations per unit input, the SLAC accelerators have had the best record, followed by the Fermilab and Brookhaven accelerators, with the CERN and DESY machines some way behind.

Probably the most useful of the indicators based on total citations is the average number of citations per paper. This again takes into account

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[30] As noted above, only citations in even years are reported here. However, the inclusion of citations made in the intervening odd years does not lead to appreciably different results.

Table 10
Relative scientific impact of major accelerators, 1969–78: Citations in relation to inputs

	Inputs [a] (% of world total)	Citations to recent papers (% of world total)
CERN	25–32 [b]	26.5
DESY	4–5 [c]	4
Brookhaven	5–7	10.5
Fermilab	11–13 [b]	19 (23.5) [d]
SLAC	5–6 [c]	14

[a] These figures have been taken from table 5, and represent an average of the figures for numbers of users and for funding.
[b] Except in the very early years of the decade, 1969–78.
[c] Except in the last year or so of the decade.
[d] Average of the totals for 1974, 1976 and 1978.

differences in the scale of resources and research activity associated with each accelerator, and enables direct comparisons to be made of the average impacts of the great mass of experimental papers that at best contribute only marginally to scientific progress. Table 11 gives the relevant data for various four-year periods between 1969 and 1980; the 1972 figures, for example, represent the number of citations in the 1972 *Science Citation Index* to experimental papers published between 1969–72, divided by the total number of those papers. In terms of this indicator, the CERN accelerators again come out behind those at SLAC and Fermilab,[31] as well as behind those at DESY, but ahead overall of the Brookhaven AGS – a relatively old accelerator yielding publications with a somewhat lower than average impact in the latter part of this period.

7. Accelerator outputs – highly cited papers and discoveries

We pointed out previously that, while indicators based on publication counts and total or average numbers of citations provide information on the vast number of small incremental contributions to scientific progress, they may reveal very little indeed about which accelerators have been responsible for the occasional crucial discoveries that have completely transformed high-energy physics. In order to focus on such discoveries (and also on slightly lower-level, but nevertheless important, advances), it is useful to examine the data on highly cited papers.[32]

First, however, the period 1969–78 needs to be set in its historical context. While several major discoveries in high-energy physics had been made in the second half of the 1950s and the early 1960s, between 1965 and 1968 there were virtually none, and from 1969 to 1972 only a few (deep-inelastic scattering at SLAC,[33] the first indications of rising total cross-section in hadron collisions at Serpukhov, and some early results from the ISR at CERN).

In contrast, the period 1973–77 resulted in numerous major discoveries – most notably those of neutral currents, the J/psi particle, the heavy lepton tau, charmed particles, and the upsilon – which completely transformed the nature of particle physics.[34] High-energy physics during this period, and in particular at the time of the so-called "November revolution" in 1974 (when the J/psi was discovered), may be seen as an epoch of truly "revolutionary" science while the previous period from 1965–72 was more one of 'normal' science (cf. Kuhn [16]).

During this revolutionary period, certain key experimental papers clearly achieved an impact many times greater than that of the great majority of other publications. It is therefore necessary to look at the distribution of highly cited papers between accelerators, since this may provide a more relevant indicator of relative contributions to scientific knowledge than total numbers of publications or citations. These data are given in table 12.

Over the decade 1969–78, approximately 5400

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[31] The high figure for the Fermilab accelerator is partly due to several controversial papers subsequently found to be "mistaken" – see the following section on highly cited papers.

[32] The only high-energy physics experiment during the 1960s to have subsequently been awarded a Nobel Prize was that which discovered CP-violation. The paper reporting this discovery was the most-cited experimental publication of that decade. Similarly, the most-cited experimental papers of the 1970s concern the discovery of the J/psi particle, and that too was rewarded by a Nobel Prize.

[33] This work was published in 1969, although the experiment had been carried out the previous year. In what follows, the dates given for experiments refer to when the results were published rather than when the experiment was run.

[34] The results from these and other experiments during the 1960s and 1970s are discussed in more detail in paper II [12].

Table 11
Average citations per paper (CPP) for journal articles published during the preceding four years

		1972	1974	1976	1978	1980	Average for 1972, 1974, 1976 and 1978
CPP for papers from W. European accelerators	CERN	2.8	4.0	3.0	3.2	3.1	3.2
	DESY	4.0	2.5	2.7	5.7	8.8	3.8
	Others	2.5	2.6	2.4	2.0	2.0	2.4
	W. European average CPP	2.8	3.5	2.9	3.2	3.7	3.1
CPP for papers from US accelerators	Brookhaven	2.9	2.5	3.2	2.7	1.6	2.8
	Fermilab	(3.8) [a]	6.9	6.7	7.3	3.7	7.0
	SLAC	4.9	4.2	7.1	5.8	4.4	5.6
	Others	2.5	2.5	2.0	2.9	3.2	2.5
	US average CPP	3.0	3.3	4.6	5.3	3.4	4.0
CPP for papers from other accelerators (Soviet Union, Japan)		1.4	1.9	1.5	1.0	1.1	1.4
World average CPP		2.7	3.1	3.3	3.5	3.0	3.2

[a] This value is based on only five papers, and may not therefore be very significant.

experimental journal articles were published. Of these, the top 0.2 percent most cited earned 100 or more citations ($n \geqslant 100$) in any one year. Examination of these 11 papers (see the final column of table 12) reveals that they correspond closely with the crucial discoveries listed above. [35] Fur-thermore, it can be seen that the SLAC accelerators produced over half of these papers (6 out of 11), many times more than the accelerators at any other centre; the CERN, Brookhaven, Fermilab and Serpukhov machines achieved only one each. Such a striking difference would suggest that, in this period of revolutionary science, the SLAC accelerators were central in advancing our knowledge of high-energy physics. [36]

It is also instructive to examine the distribution between accelerators of discoveries of a slightly lesser magnitude (the term "major advances" will be used, in distinction from "crucial discoveries") by considering the data on papers cited more than 50 and more than 30 times in a year (see the middle two columns of table 12). These correspond, respectively, to the top 0.8 percent and top 2 percent most-cited papers over the decade 1969–78. As can be seen, the Fermilab accelerator has yielded most papers at these levels, followed by the CERN and SLAC accelerators. However, it should be noted that at least four of the Fermilab papers (two on "trimuons" and two on the "high-y anomaly") earning 50 or more citations are now considered by most high-energy physicists to have been "mistaken," and to have seriously misled theorists for several years before they were refuted by more accurate results from the CERN SPS accelerator. At the time these papers appeared, high-energy physicists were beginning to regard the "Weinberg–Salam theory" as a strong candidate for a unified theory of electromagnetic and weak interactions. Yet the Fermilab results appeared to imply that the simple model of Weinberg–Salam was invalid and a more complicated version was required. For a short period thereafter, these papers, not surprisingly, had a rather high impact within the scientific community (reflected in their citation rates), as the following review article of the time makes clear:

> Perhaps *the most dramatic development* in neutrino physics in the last year or so has been the observation of substantial anomalies in the total and differential cross-sections at high-energy. ... The new data ... appear to lead *inexorably* to new quarks and new couplings, simply because other mechanisms are inadequate (Perkins [29, p. 470 and p. 475], emphasis added).

Understandably, some of those who laboured long

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[35] The degree of correspondence is examined in detail in paper II [12]. However, it is worth stressing here that *none* of the 11 is a "mistaken" paper.

[36] The same conclusion was reached in Martin and Irvine [18], but in a much more tentative form.

Table 12
Numbers[a] of highly cited papers (HCP) for the period 1969–78: Numbers of papers cited *n* or more times in one year

		$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$
HCP for	CERN	111	31	9	1
W. European		(26%)[b]	(26%)	(19.5%)	(9%)
accelerators	DESY	20	9	3	0
		(4.5%)	(7.5%)	(6.5%)	(0%)
	Others	14	4	1	1
		(3.5%)	(3.5%)	(2%)	(9%)
	Total W. Europe	145	44	13	2
		(34%)	(37%)	(28%)	(18%)
HCP for US	Brookhaven	37	6	2	1
accelerators		(8.5%)	(5%)	(4.5%)	(9%)
	Fermilab	106	37	17	1
		(24.5%)	(31%)	(37%)	(9%)
	SLAC	75	21	11	6
		(17.5%)	(17.5%)	(24%)	(54.5%)
	Others	42	7	1	0
		(10%)	(6%)	(2%)	(0%)
	Total US	260	71	31	8
		(60.5%)	(59.5%)	(67.5%)	(72.5%)
HCP for other accelerators		24	4	2	1
		(5.5%)	(3.5%)	(4.5%	(9%)
World total		429	119	46	11
		(100%)	(100%)	(100%)	(100%)

[a] These figures have been obtained by scanning the *Science Citation Index* for the years 1969 to 1982. The likely errors should be rather smaller than the 10 percent figure of previous tables.

[b] All percentages have been rounded to the nearest 0.5 percent.

and hard in constructing new theoretical models to accommodate the errant Fermilab data are now somewhat resentful that their efforts appear to have been needless.[37] One eminent theorist subsequently described the time between the first appearance of the anomalous results and their eventual refutation as

> a confusing period of exhilaration and disappointment, alarms and excursions. Experiment confirmed the [Weinberg-Salam] theory; experiment denied the theory. Enormous theoretical effort was devoted to producing grotesque mutant versions of the theory consistent with the new experimental results; the new experiments were shown to be in error; the mutants were slain. (This happened at least three times: with high-y anomalies, with trimuons, and with atomic parity violation). In the last few years, though, the experimental situation seems to have stabilized in agreement with the original 1971 version of the theory. The Weinberg-Salam model is now the standard theory of the electro-weak interaction (Coleman [6, p. 122]).

It is far from simple to decide how such "mistakes" should be assessed. Certainly, they did initially have a major impact on high-energy physics and their citation figures for the period reflect this. However, as soon as they were generally recognized to be "mistaken," their impact fell dramatically to become almost negligible. (This was reflected in their citation rates rapidly dropping to virtually zero.) With hindsight, that initial impact might now be judged to have been negative (i.e. retarding rather than advancing scientific knowledge). According to another interpretation, however, the efforts to explain these results were not in vain: thus, although the Fermilab data led theorists to posit the existence of a new, fifth type of quark for reasons that turned out to be specious, they

> nonetheless served a valuable heuristic purpose in stimulating speculation about the properties of particles composed of heavier quarks, properties the upsilon [an important new

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[37] This came across very strongly in several of the interviews that we conducted. One distinguished theorist commented: "The high-y anomaly attracted a tremendous amount of theoretical activity which was just misguided. So they did a great disservice to the high-energy physics community. They held things back by several years" (Interview, 1981).

> particle discovered a little later] turned out to have (Lederman [17, p. 67].

Under this latter interpretation, these "mistaken" papers clearly did contribute to the advance of scientific knowledge, although probably not by as much as their subsequent citation records would suggest. The Fermilab data on highly cited papers in table 12 and subsequent tables should therefore be viewed in this light.

We can go on from here to consider the distribution across accelerators of a still lower level of discoveries (the term "advances" will be used). The first column of table 12 presents data on those papers earning 15 or more citations in a year (corresponding to the top 8 percent most-cited papers). In marked contrast with the data on "crucial discoveries" and "major advances," it can be seen that the CERN accelerators produced 111 such papers, slightly more than the Fermilab accelerator (106) and significantly more than the SLAC (75), Brookhaven (37) and DESY (20) machines.

Finally, we should examine data relating to the different "lifetimes" of highly cited papers. This is a necessary dimension to any assessment of impact since it is clear that some key publications have a continuing major impact over several years, while others (most notably "mistaken" papers) are relatively short-lived. This effect can be allowed for by analyzing the number of times that highly cited papers earn more than a certain number of citations in a year. The relevant data are given in table 13. Overall, we can conclude that the pattern of distribution between the accelerators is not markedly different from that evident in table 12, although the figures for the Fermilab accelerator for papers cited 50 or more times are reduced from 37 percent to 30 percent of the respective world totals. This is largely because of the shorter lifetimes of the mistaken Fermilab papers.

How do these various data on highly cited papers relate to the inputs for the various accelerators? Table 14 presents data on relative scientific impact, setting the figures for $n \geq 15$ in table 13 against the relevant input figures. (Comparisons of inputs with data on more highly cited papers in

Table 13
Numbers of highly cited papers (HCP) for the period 1969-78: Number of times highly cited papers received n or more citations in a year [a]

		$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$
HCP for W. European accelerators	CERN	269 (27.5%) [b]	56 (23.5%)	16 (18.5%)	1 (5.5%)
	DESY	43 (4.5%)	12 (5%)	3 (3.5%)	0 (0%)
	Others	32 (3.5%)	6 (2.5%)	3 (3.5%)	2 (11%)
	Total W. Europe	344 (35%)	74 (31%)	22 (25.5%)	3 (16.5%)
HCP for US accelerators	Brookhaven	83 (8.5%)	18 (7.5%)	6 (7%)	3 (16.5%)
	Fermilab	232 (23.5%)	71 (30%)	26 (30%)	2 (11%)
	SLAC	187 (19%)	57 (24%)	27 (31%)	9 (50%)
	Others	79 (8%)	8 (3.5%)	2 (2.5%)	0 (0%)
	Total US	581 (59%)	154 (64.5%)	61 (70%)	14 (78%)
HCP for other accelerators (Soviet Union, Japan)		59 (6%)	10 (4%)	4 (4.5%)	1 (5.5%)
World total		984 (100%)	238 (100%)	87 (100%)	18 (100%)

[a] These figures have been obtained by scanning the *Science Citation Index* for the years 1969 to 1982.

[b] All percentages have been rounded to the nearest 0.5 percent.

Table 14
Relative scientific impact of major accelerators, 1969–78: Highly cited papers in relation to inputs

	Inputs[a] (% of world total)	Number of times papers earned ≥ 15 citations in a year (% of world total)
CERN	~ 25–32[b]	27.5
DESY	~ 4–5[c]	4.5
Brookhaven	~ 5–7	8.5
Fermilab	~ 11–13[b]	23.5
SLAC	~ 5–6[c]	19

[a] These figures have been taken from table 5, and represent an average of the figures for numbers of users and for funding.
[b] Except in the very early years of the decade, 1969–78.
[c] Except in the last year or so of the decade.

both tables 12 and 13 could also, of course, be made.) Again, the SLAC accelerators emerge best from this comparison of input-adjusted impact, followed by the Fermilab (but with the reservation about mistaken papers) and Brookhaven machines.

The output from the CERN accelerators in terms of this indicator (at $n \geq 15$) is little different from their share of inputs, a conclusion that needs some qualification if data on very highly cited papers ($n \geq 100$) are introduced into the comparison.

8. Accelerator outputs – peer-evaluation

Our previous studies of various Big Science specialities have strongly suggested that, while indicators based on publication and citation analysis provide essential information on the relative contributions to scientific knowledge associated with different research facilities, such indicators always need to be considered alongside peer-evaluation data. So how do high-energy physicists judge the magnitude of the contributions from the CERN accelerators compared with those from other accelerators?

Peer-evaluation data were obtained for all the accelerators included in the present study through interviews with 182[38] experimental and theoretical high-energy physicists. These were carried out in the latter part of 1981 and the first half of 1982. In selecting our interview sample, care was taken to ensure that as far as was possible the views of researchers from Western Europe, Eastern Europe and the United States were all well represented.[39] The result was that 41 high-energy physicists were interviewed at CERN, 71 in CERN user-groups in Western Europe, 28 at Brookhaven (and in the user-group at the State University of New York, Stonybrook), 24 at Fermilab, and a total of 18 in Bulgaria, Finland and Poland.

The interviews were intensive (typically lasting $1\frac{1}{2}$ to 2 hours) and structured, being based on a common set of questions but with a few additional questions for special groups of researchers. After giving brief details of their background and career, interviewees were asked to describe their own research work and perceived contributions to high-energy physics. The questions were then gradually broadened in several stages, interviewees being requested first of all to identify the principal contributions of the various collaborations in which they had worked, then those from the accelerators they had used, and, finally, the overall contributions from the world's other major accelerator facilities. In some cases, memories had to be jolted or occasionally corrected when discoveries or major research programmes were attributed to the wrong accelerators.[40] Apart from its information value, this exercise in systematically recollecting the contributions of different accelerators was useful in helping respondents prepare themselves for the peer-review section of the interview. In this, interviewees were invited to rank the accelerators at fourteen different laboratories according to the relative magnitude of their contributions to high-energy physics over the period 1969–78. (For this question, all three CERN accelerators were treated as one unit,[41] as was the case with other multi-accelerator laboratories.) In addition to the five major Western laboratories already discussed, we included in the peer-ranking three smaller facilities in the United States (Argonne; the Cambridge

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[38] This does not include a number of other interviews that were terminated prematurely when it became apparent that interviewees had insufficient knowledge to answer the questions satisfactorily, being unable, for example, to recollect correctly which accelerators were responsible for certain experimental results.

[39] See note 45, below.

[40] For example, some physicists wrongly attributed the discovery of neutral currents to the CERN SPS rather than the PS.

[41] However, it should be re-emphasized that we are here assessing the outputs from the CERN *accelerators*, not the performance of CERN as a centre nor its staff.

Electron Accelerator, CEA; and Cornell), two in Britain (the Nimrod and NINA accelerators at Rutherford and Daresbury Laboratories respectively), and four in the Soviet Union (the large accelerator at Serpukhov, and the smaller machines at Dubna, Moscow, and Yerevan). Thus all proton accelerators with an energy of 7 GeV or greater, and all electron accelerators of 4 GeV or more, operating between 1969 and 1978, [42] were included. [43]

Of the 182 physicists interviewed, relatively few were able to rank in full order from 1 (top) to 14 (bottom) the accelerators at all fourteen laboratories. Most regarded at least two or more as having made equivalent contributions, particularly in the case of those at the lower end of the order. Others preferred to identify five or six distinct groups of accelerators and then to rank these in order. Only 8 percent found it too difficult to undertake the ranking, or refused for personal or professional reasons.

Average rankings on a scale of 1 to 14 were then calculated, [44] and the results are given in table 15. [45] In addition to presenting "overall average rankings" for each research facility (see the penultimate column of the table), we have classified the judgements of the 168 high-energy physicists who provided rankings into six groups in order to establish whether interviewees' current institutional affiliation had any significant effect upon the results. These groups consist of those interviewed in (1) Brookhaven and Stonybrook; (2) Fermilab; (2) CERN; (4) research teams in three large CERN Member States (Britain, France and Italy); (5) research teams in two small CERN Member States (the Netherlands and Norway); and (6) user-groups of Soviet accelerators in Bulgaria, Finland and Poland.

Certain comments can be made about the figures in table 15. First, a high degree of consistency exists between the average rankings for each of the six groups; with just two exceptions, all are within one unit of the overall average (for all 168 interviewees), and over three-quarters are within half a unit. Second, those two exceptions are the rankings by Finnish and East European physicists of the scientific contributions associated with the Dubna and Serpukhov accelerators in the Soviet Union. Given the problems of scientific communication between East and West, this larger difference is probably due to a certain ignorance on the part of many scientists in the West of the experimental work of these accelerators. [46] Third, a small "self-ranking" effect seems to be evident in certain cases; for example, high-energy physicists interviewed at Brookhaven ranked the AGS accelerator 3.1 compared with an overall average of 3.7, while the equivalent figures for Fermilab were 2.3 and 3.1. Table 16 attempts to set out in a more explicit way the effects of self-ranking (see the first two columns); thus, the 12 interviewees who, for example, had used the Argonne accelerator ranked it 7.5 ("self-ranking") while the remaining 156 (who had not) ranked it 7.6 ("peer-ranking"). However, the effect is not, in general, sufficiently large to cast doubt on the reliability of the results this approach yields. Fourth, and finally, although a number of senior physicists interviewed felt that certain categories of physicists – in particular, older, established researchers (i.e.

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[42] Accelerators that only began to yield published results after 1978 (such as PETRA at DESY, and CESR at Cornell) have been excluded.

[43] Conversely, accelerators with less than these energies were excluded. It should be noted, however, that several of them, for example those at Berkeley, Orsay, Saclay, Frascati, and Novosibirsk, might well have been placed above some of those ranked towards the bottom of our list of fourteen had they been included.

[44] Where, for example, two accelerators were ranked first equal, they were each given the ranking 1.5 (i.e $(1+2)/2$); where three were placed first equal, they were ranked 2 (i.e. $(1+2+3)/3$); and so on.

[45] It should be stressed that these rankings were made primarily by physicists whose main research experience has been with proton accelerators. This was necessary given that the aim of the study was to evaluate the scientific outputs of the CERN accelerators in relation to their main competitors. Similarly, in our previous study of world electron accelerators, those chosen to undertake the peer-ranking exercise were mainly electron physicists. (See table XVII of Martin and Irvine [18] for the relevant results.) However, it should be noted that the results are strikingly similar, despite the different cognitive and institutional locations of the scientists making the peer-judgements. In the electron-accelerator study, only thirteen facilities were ranked (Cornell was not included), so some slight adjustment needs to be made to the rankings in order to compare the results directly.

[46] The difference between the East European rankings of the Dubna and Serpukhov accelerators and the "overall average" rankings is much bigger than the "self-ranking" effects (see text above) in the results for Western accelerators. This suggests that at least part of the difference must be attributed to an "ignorance" effect. See Irvine and Martin [11] for further discussion.

Table 15

Peer-evaluation rankings[a] of the contributions to high-energy physics[b] made by accelerators at 14 laboratories between 1969 and 1978

Accelerator(s) (energy)	Peer-evaluation rankings[c] by high-energy physicists in						Overall average rankings	Relative position
	Brookhaven and Stonybrook	Fermilab	CERN	Large CERN Member States	Small CERN Member States	Bulgaria, Finland Poland		
(Sample size)	(26)	(23)	(39)	(45)	(21)	(14)	(168)	
Proton machines								
Argonne ZGS	6.9	6.6	8.5	7.6	7.6	7.8	7.6	6
(12 GeV)	(±0.3)	(±0.2)	(±0.3)	(±0.3)	(±0.4)	(±0.5)	(±0.1)	
Brookhaven AGS	3.1	4.1	3.9	3.7	3.4	3.6	3.7	4
(33 GeV)	(±0.2)	(±0.2)	(±0.2)	(±0.2)	(±0.3)	(±0.3)	(±0.1)	
CERN (i) PS (28 GeV)								
(ii) ISR(31 + 31 GeV)	2.5	3.7	2.3	2.4	2.3	2.0	2.4	2
(iii) SPS (400 GeV)	(±0.1)	(±0.1)	(±0.1)	(±0.1)	(±0.2)	(±0.2)	±0.1)	
Dubna	11.9	12.2	11.8	11.4	11.0	10.3	11.5	12
(10 GeV)	(±0.3)	(±0.2)	(±0.2)	(±0.2)	(±0.3)	(±0.5)	(±0.1)	
Fermilab	3.3	2.3	3.1	3.4	3.6	3.0	3.1	3
(400 GeV)	(±0.1)	(±0.2)	(±0.1)	(±0.1)	(±0.2)	(±0.3)	(±0.1)	
Moscow ITEP	12.1	13.0	12.2	12.1	11.8	12.2	12.2	13 =
(7 GeV)	(±0.3)	(±0.1)	(±0.2)	(±0.2)	(±0.3)	(±0.3)	(±0.1)	
Rutherford Nimrod	9.1	9.4	8.9	8.6	9.9	10.1	9.1	9 = [d]
(7 GeV)	(±0.4)	(±0.3)	(±0.2)	(±0.3)	(±0.3)	(±0.5)	(±0.1)	
Serpukhov	9.4	8.6	9.1	8.9	7.8	7.1	8.7	7 = [d]
(70 GeV)	(±0.4)	(±0.3)	(±0.3)	(±0.3)	(±0.5)	(±0.6)	(±0.2)	
Electron machines								
CEA (i) 6 GeV	9.0	8.7	9.0	9.1	10.1	10.2	9.2	9 = [d]
(ii) BYPASS (3 + 3 GeV)	(±0.3)	(±0.5)	(±0.3)	(±0.3)	(±0.3)	(±0.4)	(±0.1)	
Cornell	8.4	7.9	8.1	8.9	8.6	9.1	8.5	7 = [d]
(12 GeV)	(±0.3)	(±0.3)	(±0.3)	(±0.3)	(±0.5)	(±0.5)	(±0.1)	
Daresbury NINA	9.6	10.7	9.5	9.7	10.5	10.7	10.0	11
(4 GeV)	(±0.3)	(±0.3)	(±0.3)	(±0.2)	(±0.3)	(±0.5)	(±0.1)	
DESY (i) (7 GeV)	6.3	5.0	5.0	5.7	4.9	5.4	5.4	5
(ii) DORIS (5 + 5 GeV)	(±0.4)	(±0.2)	(±0.2)	(±0.3)	(±0.3)	(±0.3)	(±0.1)	
SLAC (i) (20 GeV)	1.3	1.3	1.3	1.1	1.4	1.6	1.3	1
(ii) SPEAR (4 + 4 GeV)	(±0.1)	(±0.1)	(±0.1)	(±0.1)	(±0.1)	(±0.2)	(±0.1)	
Yerevan	12.1	12.5	12.3	12.3	12.1	11.9	12.2	13 =
(6 GeV)	(±0.2)	(±0.3)	(±0.2)	(±0.2)	(±0.3)	(±0.4)	(±0.1)	

[a] 1 = highest ranking; 14 = lowest ranking.

[b] Contributions to other areas of research such as nuclear physics or synchrotron radiation are *not* being assessed here.

[c] The figure in brackets indicate the root-mean-square variations between the assessments made by the high-energy physicists, giving some approximate idea of the divergence of opinion within the different groups.

[d] Differences of only 0.1 or 0.2 in the overall average rankings are not statistically significant.

those who have been active for 15 or 20 years), theorists (who are generally less "committed" to particular accelerator centres), and experimentalists who had used a large number of accelerators – would be likely to give more balanced and reliable rankings, we found little evidence that this was the case. In this respect, table 16 (final two columns) considers the rankings made by those gaining their Ph.D. degrees before and after 1965, while table 17 presents data on the judgements made by theorists as well as figures "weighting" individual physicists' rankings by the number of accelerators used. As can be seen, these groups of researchers hold relatively similar views on accelerator performance to those of high-energy physicists in general.

Table 16

Rankings[a] of accelerators for 1969 to 1978: Effects of self-ranking and age[a]

Accelerator(s) (energy)	Self-ranking	Peer-ranking	Ph.D. awarded before (or during) 1965 (n = 89)	Ph.D. after 1965 (or no Ph. D.) (n = 79)
Proton machines				
Argonne ZGS (12 GeV)	7.5(± 0.5) (n = 12)	7.6(± 0.1) (n = 156)	7.7(± 0.2)	7.5(± 0.2)
Brookhaven AGS (33 GeV)	3.5(± 0.2) (n = 47)	3.7(± 0.1) (n = 121)	3.8(± 0.1)	3.5(± 0.1)
CERN (i) PS (28 GeV) (ii) ISR (31 + 31 GeV) (iii) SPS (400 GeV)	2.3(± 0.1)	2.6(± 0.1)	2.3(± 0.1) (n = 108)	2.6(± 0.1) (n = 60)
Dubna (10 GeV)	11.2(± 0.4) (n = 9)	11.5(± 0.1) (n = 159)	11.6(± 0.2)	11.4(± 0.2)
Fermilab (400 GeV)	2.6(± 0.1) (n = 45)	3.3(± 0.1) (n = 123)	3.1(± 0.1)	3.2(± 0.1)
Moscow ITEP (7 GeV)	–	12.2(± 0.1) (n = 168)	12.2(± 0.1)	12.2(± 0.1)
Rutherford Nimrod (7 GeV)	7.5(± 0.4) (n = 23)	9.4(± 0.1) (n = 145)	8.8(± 0.2)	9.5(± 0.2)
Serpukhov (70 GeV)	6.7(± 0.4) (n = 19)	9.0(± 0.2) (n = 149)	8.7(± 0.2)	8.7(± 0.2)
Electron machines				
CEA (i) 6 GeV (ii) BYPASS (3 + 3 GeV)	–	9.2(± 0.1) (n = 165)	9.3(± 0.2)	9.1(± 0.2)
Cornell (12 GeV)	–	8.5(± 0.1) (n = 165)	8.4(± 0.2)	8.5(± 0.2)
Daresbury NINA (4 GeV)	–	10.0(± 0.1) (n = 163)	9.9(± 0.2)	10.0(± 0.2)
DESY (i) 7 GeV (ii) DORIS (5 + 5 GeV)	5.1(± 0.4) (n = 17)	5.4(± 0.1) (n = 151)	5.5(± 0.2)	5.3(± 0.2)
SLAC (i) 20 GeV (ii) SPEAR (4 + 4 GeV)	1.1(± 0.1) (n = 17)	1.3(± 0.1) (n = 151)	1.3(± 0.1)	1.2(± 0.1)
Yerevan (6 GeV)	–	12.2(± 0.1) (n = 168)	12.2(± 0.1)	12.3(± 0.1)

[a] 1 = highest ranking; 14 = lowest ranking. The figures in brackets indicate the root-mean-square variations between the assessments made by the high-energy physicists, giving some approximate idea of the divergence of opinion within the different groups.

[b] The sample size of each group is denoted by n.

One of the main difficulties with peer-evaluation is, of course, the problem of overcoming researchers' natural worries about the implications for themselves and colleagues of negative judgements, particularly in a period of financial pressure on funding bodies.[47] However, given the comparatively small systematic variations found in the rankings made by the very different groups of high-energy physicists, it would seem fair to conclude that this problem has largely been overcome by our peer-evaluation technique, and that a certain degree of confidence can be placed in the results. This said, we are now in a position to summarize the peer-review findings. The final column of table 15 converts the overall average rankings made by physicists back into the relative positions of the accelerators at the fourteen laboratories. The clear conclusion here is that the SLAC accelerators are regarded as having contributed most to the advance of high-energy physics over the period 1969–78 (see note a to table 15), followed by the accelerators at CERN, Fermilab,

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[47] See Irvine and Martin [13] for a discussion of the problems that now confront peer-review as a mechanism for scientific management.

Table 17
Rankings of accelerators [a] for 1969 to 1978: Views of theorists and rankings weighted by number of accelerators used [b]

Accelerator(s) (energy)	Theorists (n = 21)	Rankings weighted by number of accelerators used	Overall unweighted average rankings (n = 168)
Proton machines			
Argonne ZGS (12 GeV)	8.2(± 0.4)	7.6(± 0.1)	7.6(± 0.1)
Brookhaven AGS (33 GeV)	3.3(± 0.2)	3.8(± 0.1)	3.7(± 0.1)
CERN (i) PS (28 GeV) (ii) ISR (31 + 31 GeV) (iii) SPS (400 GeV)	2.3(± 0.1)	2.4 [c]	2.4(± 0.1)
Dubna (10 GeV)	11.1(± 0.4)	11.6(± 0.1)	11.5(± 0.1)
Fermilab (400 GeV)	3.5(± 0.2)	3.1 [c]	3.1(± 0.1)
Moscow ITEP (7 GeV)	11.9(± 0.3)	12.4(± 0.1)	12.2(± 0.1)
Rutherford Nimrod (7 GeV)	9.8(± 0.4)	8.9(± 0.1)	9.1(± 0.1)
Serpukhov (70 GeV)	8.1(± 0.5)	8.7(± 0.1)	8.7(± 0.2)
Electron machines			
CEA (i) 6 GeV (ii) BYPASS (3 + 3 GeV)	9.1(± 0.3)	9.3(± 0.1)	9.2(± 0.1)
Cornell (12 GeV)	8.9(± 0.4)	8.5(± 0.1)	8.5(± 0.1)
Daresbury NINA (4 GeV)	10.1(± 0.3)	9.9(± 0.1)	10.0(± 0.1)
DESY (i) 7 GeV (ii) DORIS (5 + 5 GeV)	5.5(± 0.4)	5.3(± 0.1)	5.4(± 0.1)
SLAC (i) 20 GeV (ii SPEAR (4 + 4 GeV)	1.2(± 0.1)	1.3 [c]	1.3(± 0.1)
Yerevan (6 GeV)	11.9(± 0.3)	12.4(± 0.1)	12.2(± 0.1)

[a] 1 = highest ranking; 14 = lowest ranking. The figures in brackets indicate the root-mean-square variations between the assessments made by the high-energy physicists, giving some approximate idea of the divergence of opinion within the different groups.

[b] The sample size of each group is denoted by n.

[c] Root-mean-square variation of less than 0.05.

Brookhaven and DESY, in that order. As stated earlier (note 45), these findings are closely in line with the opinions of electron high-energy physicists reported in Martin and Irvine [18].

9. Accelerator outputs – an overall assessment of the period 1969–78

In concluding our assessment, it is necessary to consider the overall picture of the relative scientific performance between 1969 and 1978 of the CERN accelerators and their users that is provided by the different partial indicators taken together. Table 18 summarizes the results for the five main Western laboratories. The CERN accelerators, for example, have been responsible for the greatest number of publications and citations, and, in terms of these two indicators, their relative position is therefore first. However, in terms of citations per paper the CERN accelerators come behind the Fermilab, SLAC, and DESY machines, in fourth position for the ten years under consideration.

The peer-evaluation results represent the views of scientists who, in according relative positions to laboratories, have tried to balance small numbers of crucial discoveries (for which the number of papers cited 100 or more times in a year provides a useful indicator) against overwhelmingly greater numbers of lower-level contributions (for which citation totals provide a reasonable indication of overall impact).[48] Thus, it is notable that, while the CERN accelerators rank highest in terms of both total citations and "advances" (papers cited 15 or more times in a year), the physicists interviewed nevertheless ranked them second for the decade in question, behind the SLAC machines. This suggests that, in considering a period which witnessed revolutionary change in their subject, they attached greater weight to the criterion of whether or not accelerators have been responsible for the "crucial discoveries" that transformed the field. In line with the figures on very highly-cited papers ($n \geqslant 100$) showing SLAC as having been responsible for over half such crucial discoveries, they ranked the Stanford accelerators ahead of those at CERN. In addition, among the five facilities, only DESY apparently failed to produce a single such crucial discovery during the period concerned,[49] and those interviewed ranked it fifth. The CERN, Brookhaven and Fermilab facilities cannot be distinguished in terms of crucial discoveries (between 1969 and 1978, each yielded one paper cited more than 100 times); however, the indicators of lower-level contributions (based on total citations and "advances") both suggest that Fermilab should be ranked ahead of Brookhaven, but behind CERN, agreeing with the relative positions accorded to these three by the peer-reviewers.

In the light of these results, certain comments should perhaps be made about the notion of "convergence" between partial indicators that was introduced in our earlier work on assessing large basic research facilities (particularly in Martin and Irvine [19]). It is clear that, in the present study, the indicators do not all converge, and the set of indicators used needs to be interpreted with some care. In part, this lack of overall convergence is due to the fact that the various facilities being compared differ rather more in terms of their relative sizes and inputs than those examined previously.[50] But probably more important is the fact that, in a field of science undergoing a period of revolutionary change, as did high-energy physics during the mid-1970s, indicators based on publication and citation totals lose much of their utility since they tend not to reveal where the crucial discoveries were made. Citations per paper can also be misleading unless great care is taken to identify, and allow for, the rather greater numbers of "mistaken" papers that appear to surface during such periods of theoretical uncertainty. Even

Table 18
Accelerator output, 1969–78: Summary of the relative positions[a] suggested by the various partial indicators

	Publications	Total citations	Citations per paper	"Advances"[b]	"Crucial discoveries"[c]	Peer-evaluation
CERN	1	1	4	1	3 =	2
DESY	5	5	3	5	5	5
Brookhaven	2	4	5	4	3 =	4
Fermilab	3	2	1	2	3 =	3
SLAC	4	3	2	3	1	1

[a] 1 = highest ranking; 5 = lowest ranking.
[b] Based on the number of papers cited 15 or more times in a year (the top 8 percent most-cited papers).
[c] Based on the number of papers cited 100 or more times in a year (the 0.2 percent most-cited papers).

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[48] In paper II [12] we present the results of a further peer-evaluation study in which high-energy physicists were requested to distinguish between these two criteria in assessing the output of the world's six largest proton-accelerators.

[49] The DESY machines were, however, responsible for several lower-level but nonetheless major advances: the discovery of the decay of the psi prime to the psi via an intermediate state, and confirmation of the discoveries of the upsilon, upsilon prime and charmed F mesons. Moreover, since the end of 1978, PETRA has been responsible for several very important advances such as the discovery of 3-jet events.

[50] For example, CERN currently offers a greater range of facilities than Fermilab and Brookhaven combined.

the results based on highly cited papers are not completely satisfactory, since slightly different answers are obtained according to whether one focuses on "crucial discoveries", "major advances," or "advances." For a subject in the throes of revolutionary change, the first of these yields results that are most consistent with peer-evaluation. However, it is somewhat limited as an indicator because the statistics on crucial discoveries are small; while it may, therefore, be used to identify the leader(s) in the field, it is unlikely to discriminate clearly between the great majority of the research facilities being assessed.

From this, various conclusions can be drawn. First, it is not possible to carry out assessments of relative scientific outputs on the basis of a single bibliometric indicator (for example, publication or citation totals). To attempt to do so may lead to results that are seriously misleading. Second, even when several indicators are used together, one cannot adopt a "mechanical" approach whereby publication and citation data are computed and assumed to reveal in a faithful manner all aspects of the output from different research facilities. The results based on each indicator need to be carefully *interpreted*, as has been clearly demonstrated above.[51] Finally, it needs to be recognized that careful interpretation is only possible on the basis of detailed inside information on the research field under consideration, information that is accessible to "outsiders," such as policy-researchers, only through intensive interviewing of the type described earlier. Even if it is impossible to obtain quantitative peer-evaluation data (as we were unable to do for some aspects of experimental high-energy physics before 1969), qualitative data are still absolutely essential if one is to ensure that the various pitfalls associated with each of the bibliometric indicators are to be safely negotiated.

This concludes the first part of our assessment of the high-energy physics facilities operated by CERN. We have seen how the method of converging partial indicators can be used – admittedly only with great care – to yield what appear to be reasonable results comparing the overall output of the CERN accelerators with that of other major high-energy physics facilities over the period 1969–78. It seems clear that, over this period, users of the CERN accelerators contributed less to the advance of scientific knowledge than those of SLAC, but more than those of any other experimental centre. However, if we take into account the differing levels of resources invested in each accelerator laboratory (see tables 8 and 10), then the users of all three US national accelerator laboratories appear to have a better record over the ten years in question than those of CERN.[52] In paper II [12], we look more closely at the performance of the individual CERN accelerators, at the changes in their performance over time, especially in the period since 1978, and at the factors explaining their performance relative to that of other major accelerators around the world.

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[51] As a result, we would argue that there is little point in attempting to calculate correlation coefficients between the results based on different indicators – this would be more misleading than useful because it might suggest spurious precision.

[52] In paper II, we shall see how the situation has changed very significantly during the early 1980s, particularly as a result of the discoveries at CERN of the two Intermediate Vector Bosons.

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