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STUDIES IN CERN HISTORY

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**THE INTERSECTING STORAGE RINGS:
THE CONSTRUCTION AND OPERATION OF CERN'S SECOND LARGE
MACHINE AND A SURVEY OF ITS EXPERIMENTAL PROGRAMME ¹**

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The Intersecting Storage Rings (ISR) project was unanimously approved by the CERN Council in June 1965, as the outcome of a long and controversial decision making process which was analyzed in detail in the previous volume.² The construction of the machine started in early 1966 and it was commissioned for physics experiments in March 1971. Then the ISR was in operation for about 13 years, the last run being completed in December 1983.

The ISR was a machine of a completely different design from standard proton accelerators. In the latter, in fact, a beam of accelerated protons is driven to collide against a target and the events produced by the collision are either studied as such or, more often, used to create secondary beams of particles (usually mesons) to study particular physical processes. In the ISR, on the contrary, two beams of protons each accelerated to energies up to 28 GeV by the CERN proton synchrotron were brought into virtually head-on collisions. The ISR, in fact, was the first proton-proton collider and it was to remain the only one. Before it only a

¹ All documents cited in this paper could be found in the CERN's central archive except a few that were still stored in the archive of the former ISR Department but were due to be moved to the central archive. The most important set of documents is the series of documents of the ISR Committee (ISRC), coded as CERN/ISRC/yy-nn, where yy is the year of issue and nn is a running number. A copy of these documents, except the minutes of meetings, can be found in K. Potter's files at CERN's central archive. Copies of the minutes of meetings of the ISRC, from the second (11-12/2/69) to the 67th (1/9/76), are in the file EWDS 22302 and, from the 53rd (11/12/74) to the 81st (9-10/1/79), in the file WOL 23242. The author is greatly indebted to CERN's archivist R. Rahmy for help and cooperation. While the author bears all responsibility for the opinions expressed in this paper, he must acknowledge helpful information and comments received from several people involved in the history of the ISR: M. Albrow, U. Amaldi, F. Bonaudi, L. Camilleri, P. Darriulat, L. Di Lella, G. Goggi, M. Jacob, K. Johnsen, F. Pastore, J. Steinberger. Last but not least, the author would like to acknowledge J. Krige's collaboration during the whole time he was engaged in this work.

² Pestre (1990 b).

very limited experience existed on electron-positron colliders (ADONE in Frascati, Italy, and the e^+e^- facility in Cambridge, Mass.). Subsequently, alongside several e^+e^- colliders, only two proton-antiproton colliders have been realized, at the CERN SPS and at the Fermilab Tevatron respectively.³

Due to the novelty of the conception and to the high sophistication of the technical design, the construction of the ISR was a challenging undertaking for CERN's engineers and accelerator physicists who had to obtain the best performance from all components of the machine. The operation of the facility, as well, was a matter of considerable complexity and required a quite new organization of experimental work. Physicists were not just confronted with a new accelerator but with a machine of a completely different kind from those with which they were used to performing experiments and they had to learn how to do physics with it. This represented at one at the same time a fascinating prospect and a worrying unknown; ISR results could eventually provide a scientific breakthrough as well as a bitter disappointment.

The ISR was also CERN's second large machine. After more than 11 years of exploitation of the 28 GeV proton-synchrotron (PS), a new facility was available to European particle physicists in their search for the ultimate laws of nature and in the competition with their American colleagues. The latter had also considered the idea of building a proton-proton collider in the United States but eventually abandoned it and directed all efforts towards the 500 GeV proton-synchrotron under construction at a new national laboratory near Chicago (later called Fermi National Accelerator Laboratory, or Fermilab for short). This was scheduled for commissioning in 1972, one year after the ISR.

European physicists had also advocated the construction on this side of the Atlantic of a large proton-synchrotron, the machine they considered by far the best option for the new generation of particle accelerators, but their expectations had been frustrated by political and financial constraints. Most of them did not like the ISR, which was on the contrary the favourite of CERN engineers and accelerator physicists, and they had eventually accepted the decision to build it

³ The project for a second pp collider, called *Isabelle*, had been discussed since 1972 at Brookhaven and construction began in 1978. Due to technical difficulties and cost escalations, and also because it became redundant after CERN commissioned the pp- Collider, the project was abandoned in 1983.

only when it became clear that there was no way to get the money they needed to build the 300 GeV proton-synchrotron.⁴ The ISR promised a much higher centre-of-mass energy – it was equivalent to that available in a 2000 GeV fixed target accelerator – but, on the other hand, it suffered a strong limitation in the luminosity and in the kind of processes which could be investigated – actually only proton-proton collisions. Here was the challenge European physicists had to confront.

The history of the ISR is certainly the history of a great technological success but the physics made with it can only be considered against the background of particle physics in the 1970s and with reference to the perception that particle physicists had of the development of their discipline. CERN's physicists were not only confronted with a completely new machine; they had also to tune their experimental programme with the rapid development of the field. In the period of operation of the ISR, in fact, particle physics passed through a dramatic change which reshaped both the theoretical framework and the experimental practice. Hard-scattering experiments provided compelling evidence of an internal structure of the proton, thus giving an experimental foundation to the quark hypothesis. As a consequence, new theories of quarks and leptons began to be formulated, within the context of a theoretical approach known as *gauge theory*. In particular, it was suggested that electromagnetic and weak interactions could be seen as manifestations of a single *electroweak* force. This electroweak theory was dramatically confirmed by the discovery of the *weak neutral current*, in 1973, and by the discovery of the *charm* quark, in 1974. At the same time, a particular gauge theory, called *quantum chromodynamics* (QCD), was also suggested for strong interactions of quarks, which proved to be capable of explaining the properties of hadronic phenomena and soon became the accepted theory of the strong interactions. In the late 1970s,

Particle physicists were agreed that the world of elementary particles was one of quarks and leptons interacting according to the dictates of the twin gauge theories: electroweak theory and QCD.⁵

⁴ Pestre (1990).

⁵ Pickering (1984), p. 5.

In order to cope with this changing landscape using the ISR, a new experimental philosophy had to be developed, based on large and sophisticated detectors and searching for rare phenomena at large angles. It took time, probably more than necessary, to understand that complex detectors of new conception were needed at the ISR and this was the cause of the machine's missing important discoveries and being late in finding its proper place in the mainstream of experimental particle physics in the 1970s. Thus the history of the ISR must give account not only of a great technological success and of important physical results but also of malaise and disappointments. And when writing this history, one is inevitably reminded of two famous lines from Shakespeare which a leading theoretical physicist of CERN used as an introduction to his review of ISR physics when the machine came to be closed:

The evil that men do lives after them,
The good is oft interred with their bones.⁶

This chapter is organized in four main parts. After an introductory section describing the general characteristics of the ISR, the first part deals with the discussions and controversies within the CERN's bodies to find a proper institutional arrangement for the ISR project. This problem, in fact, delayed almost one year the actual start of the construction of the machine. The second part will describe the construction of the ISR, dealing with the different aspects of the realization of such an extremely demanding technological undertaking.

In the third part, one can find a presentation of a few important aspects related to the organization of the research work at the ISR, beginning with the institutional framework set up to deal with the experimental programme (the ISR Committee). We continue with the description of the major experimental facility realized at the ISR, the so-called *Split-Field Magnet* (SFM). Then we will describe the experimental programme approved for the first phase of operation of the machine and, to close, we will discuss a few aspects of the early experimental approach to ISR physics (eventually called *keyhole physics*) which were to affect the overall scientific performance of the machine.

The fourth part will discuss ISR physics, dealing in more detail with the first half of its lifetime. This discussion is preceded by a review of the development of

⁶ Jacob (1984), p. 24.

particle physics in the 1970s which helps to understand the how and why of the ISR achievements and setbacks.

A few technical essentials about the ISR

In order to understand better the problems connected to the construction of the ISR and to its operation for physics experiments, it may be useful to give a short description of the machine and how it was operated.⁷

A first aspect to be considered is the energy motivation for this kind of device. Experiments with conventional accelerators involve the analysis of the phenomena produced by a collision between a particle in the primary or in a secondary beam of the accelerator and a stationary particle in a target. The energy available for producing the phenomena of interest is the centre-of-mass energy of the system which, in this case, is only a fraction of the energy of the incoming particle. The rest is shared as kinetic energy among the particles which result from the interaction. At high energy, if the two colliding particles are the same, as in the case of a proton beam hitting a stationary hydrogen target (or protons inside heavier nuclei), the available centre-of-mass energy is given approximately by the formula:

$$E_{\text{cm}} = \sqrt{2mc^2E}$$

where E is the energy of the beam, m the mass of the particle and c the speed of light.

If, on the contrary, two particles of energies E_1 and E_2 collide head-on, all the energy given to them can go into the phenomena of interest of physicists, i.e. the transformation of particles and the creation of new particles. In this case, in fact, the centre-of-mass energy is approximately:

$$E_{\text{cm}} = 2\sqrt{E_1E_2}$$

and, if the energy of the two colliding particles is the same ($E_1 = E_2$), the centre-of-mass energy is just twice this energy.

The energy advantage of colliding beam devices can be appreciated considering that if a 28 GeV proton beam of the CERN proton synchrotron (PS)

⁷ This description is essentially based on ISR (1974).

bombards a stationary hydrogen target, the available energy is only 7.5 GeV while, if two beams of 28 GeV are brought to collide, the available energy is 56 GeV, that is the equivalent of a conventional accelerator of 1800 GeV. This gives the possibility of studying some very high energy interactions at a much lower price than with an accelerator of equivalent interaction energy.

Against this energy advantage in colliding beam machines, there is a severe limitation in the range of phenomena which can be studied and in the rate at which the phenomena occur. First of all the particle density in a beam is much lower than in a stationary target and then, in order to obtain an interaction rate high enough to make colliding beam experiments feasible, it is necessary to build up very intense particle beams by a stacking process and to store the beams for long periods of time. A consequence is that only relatively stable particles can be used. Furthermore, in colliding beam devices, it is possible to study only phenomena produced in the collisions of the circulating particles, proton-proton collisions in the case of ISR, while in conventional accelerators a copious supply of different particles can be provided in the secondary beams.

The ISR consisted of two interlaced, slightly distorted concentric rings in which protons provided by the PS travelled in opposite directions and could be brought into collision in eight intersection regions denoted I-1 to I-8 (fig. 1). Each crossing region was in the middle of a long straight section of about 17 meters and the angle of crossing was about 15° . The diameter of the rings was 300 metres, namely 1 times that of the PS. The two rings were quite independent; therefore they could be run at different energies in order to make the centre of mass move in either direction at will. The rings were housed in a single underground tunnel located some 300 metres away from the PS. Beam-transfer lines guided the protons ejected from the PS and bent them into either of the two rings. Table 1 lists the main parameters of the ISR.

In normal ISR operations, protons were accelerated in the PS to the required energy, normally between 11 and 26.5 GeV (with the possibility of further acceleration to 31.4 GeV in the ISR), and then they were injected into a transfer channel where magnets guided them towards one or the other of the rings. A fast injection system injected the protons initially into an orbit close to the inside wall of the ring vacuum chamber. A radio frequency system was used to get hold of the protons as they came in and to accelerate them slightly so that they moved

horizontally across the beam pipe of the ISR to an orbit nearer the outside wall in order to leave the injection orbit free for another pulse of PS protons. This, in turn, was accelerated and moved to an orbit only a fraction of a millimetre from where the first pulse had been left. This stacking process was repeated again and again in order to create a stacked beam about 50 mm wide and then a sufficient intensity for physics experiments (fig. 2).

The time required to stack each ring with a beam current up to 20 A was slightly less than an hour and then colliding beam experiments could be carried out for many hours before calling on the PS again for a refill. In order to keep beams of sufficient intensity for a long time, the vacuum chamber in which the protons circulated had to be evacuated to a very low pressure (less than 10^{-11} torr) so as to avoid collisions with gas molecules in the chamber resulting in the protons being scattered in the course of many millions of revolutions.

Because of the high intensity and energy of the individual beams, the machine needed to be well protected against radioactivity hazards and special dumping systems were set up at intersection I-3 by kicker magnets giving the beams a vertical deflection into titanium alloy blocks. Intersection I-5 was permanently used for machine studies while at intersections I-1 and I-4, two large experimental halls were available. In the latter, in particular, a large magnet system had been built, called Split Field Magnet, and it was used as a general purpose facility for experiments. At other intersections, the setting up of experiments was possible in the available width of the tunnel.

By early 1974, three years after the commissioning of the machine, the ISR operated for about 3000 hours per year, of which about 2200 hours was for colliding beam physics and the preparation for it, and the rest for studies of machine performance and development. Table 2 shows the distribution in time during 1973 for experiments at the standard operating momenta, and the values for beam currents and luminosities.

Scheduling of ISR operation had to be co-ordinated with that of its injector, the PS, and special care had to be taken to minimize interference between the physics done with the two machines. Setting up normally took about two hours. The first step was to eject the PS beam into the transfer line from where it was then injected into either of the two rings. Optimization of the injection trajectories in the rings generally took about one hour. The acceleration cycle was then

adjusted and all secondary devices were adjusted. After setting up, the machine was ready for a development run or for filling for colliding beam physics. A machine development run took place once or twice per week and lasted 10 to 20 hours. It involved machine performance studies and tests of equipment and techniques aimed at improving performance and developing special conditions for physics experiments. Filling required a continuous draw of protons with definite energy from the PS and this operation was usually done in a beam sharing mode whereby the ISR took only every third PS pulse so that other PS users could continue their experiments simultaneously. The process went on until a beam with the desired intensity had been stacked, typically one hour.

Each physics run was usually preceded by a luminosity measurement at lower intensity (around 5 A). Stacks with the desired intensity were then completed in both rings and their position in each intersection region carefully adjusted in order to optimize the interaction rate against background. Optimization work took about 1 to 2 hours and then the beams were declared stable and the machine was ready for experiments. These were coded in the form RINN, where R stands for Rings, I denotes the intersection where the experiment was carried out, and NN is the running number of the experiment. A physics run usually lasted between 10 and 40 hours, followed by a shut-down of about two hours to allow controlled access to the tunnel for experimenters to check and adjust their equipment. The machine was then started up again for a new physics run with the same or different beam conditions. This sequence was repeated on about a 24-hour basis for a period of 2 or 3 weeks. Fig. 3 shows a typical weekly schedule for ISR operation.⁸

An important aspect of ISR operation, unlike that of a standard accelerator, must be mentioned here. In the latter case, by making the accelerated particles of the primary beam hit a target, other kinds of particles are produced which can be used to build up secondary beams. These are taken out from the machine and driven to different experimental halls for various investigations. Each group can operate quite independently from the others: when the machine is working it can turn on and off its particular beam, arrange its experimental apparatus and organize the work of its members. This was not the case for the Intersecting Storage Rings where all experiments shared the same (colliding) beams at the

⁸ A complete set from February 1972 to August 1976 can be found in EWDS 22321.

same time and possibly two, three or even four groups shared the same experimental area around one of the interaction regions. Moreover, all or most of the experimental equipment was inside the tunnel; as a consequence, work on any of the instruments could be done only after turning off the ISR and the run could be resumed only after the rings had been recharged from the PS. The experimental activity around the ISR was then an integrated set of operations, whose planning and management involved at the same time the definition of the experimental requirements, the technical operation of the machine, its coordination with the PS, the coordination of the different experimental groups, and the optimization in the use of time, space and technical facilities.

In a certain sense the ISR had the characteristics both of an accelerator serving several independent experimental groups and of a big experimental facility used jointly by them. This required a special kind of organization and management of the experimental activity around the machine and a high degree of integration of technical and scientific operations. At the same time this also stimulated much collaboration and a continuous exchange of information among the various teams involved in ISR experiments, which openly shared their problems and findings, as well as between them and the theorists. This was soon institutionalized in the form of a series of "ISR discussion meetings between experimentalists and theorists" which were held more or less regularly every two or three months on a particular subject and represented a novel and probably unique phenomenon at CERN.⁹

Getting started

The ISR project, aimed at building CERN's second big accelerator, was approved as a supplementary programme according to article 2 of the CERN Convention, which distinguished between the "basic" programme, involving the construction and operation of the laboratory and its first accelerators (the 600 MeV synchro-cyclotron and the 28 GeV proton synchrotron), and any additional "supplementary" programme, covering projects and initiatives to be decided on in the future. While the former had been agreed by all Member States and all were

⁹ Reports on these meetings are in the ISR archive.

financially responsible for it, the starting of a supplementary programme required the approval of a two-thirds majority of Member States but only those who decided to join it were financially responsible for its implementation.¹⁰

After December 1964, when an agreement on the building of the ISR was finally reached at scientific and political level, it required almost one year to settle all the legal and financial aspects related to the establishment, management and control of such a supplementary programme within the institutional framework of CERN. For the first time since the creation of the Laboratory, a new big machine, new major equipment, new research programmes were to be added to it and, in principle, not all Member States were to become involved in the undertaking. Moreover, one must recall that the building of the ISR involved the crossing of the Swiss–French border, which posed delicate legal problems. This happened at a very critical phase of CERN's administrative and financial history, when the new budgetary procedures set up after the recommendations of the Bannier Working Party were passing their first test under the urgency of decisions on the future development of the Organization after the fulfillment of its initial programme.¹¹ Laborious negotiations were necessary in order to find agreement on the formalities required for adhesion of Member States, on the conditions under which a Member State could join the programme at a later date or withdraw from it during the construction period, on the procedures for establishing and approving the budget, on the relationship between the supplementary programme and the basic one and on the means of managing and controlling both. These negotiations caused much stress and eventually seemed to jeopardize the project itself before its very beginning.

The problem of voting majority

In order to cope with institutional and legal problems and to present solutions within the framework of the Convention, a special working party of legal experts was created by the Finance Committee in February 1965.¹² The issues, however,

¹⁰ For this distinction see Krige (1987), p. 246–249.

¹¹ Krige (1990).

¹² Finance Committee, 65th meeting (10/2/65), CERN/FC/753/Draft, 16/3/65. See also CERN/FC/745, 20/1/65, and CERN/538, 13/5/64. The Working Group met in Paris on 2–3 March

proved to extend well beyond the legal limits when a number of Member States, led by Italy and the United Kingdom, stressed that, with the addition of the ISR project to the already growing basic programme budget, there should be a tighter control over future expenditure.¹³ As a consequence, the extraordinary Council meeting called in March to decide on starting the ISR supplementary programme could do nothing but register the negative attitude of Italy and the United Kingdom and refrain from taking any decision before the whole matter was first discussed and settled in the Finance Committee.¹⁴

G.H. Hampton, CERN's Director of Administration, took charge of the difficult task of working out a procedure for the control of the ISR supplementary programme acceptable by national delegations without undertaking the long and complex procedures required to amend the Convention. He was quite aware that the main difficulties would come from the United Kingdom and he therefore first sought approval from the Italians before confronting the British. As he wrote to the German delegate and chairman of the Finance Committee, W. Schulte-Meermann:

I would prefer to tackle the question this way because I am afraid that if we put the British and the Italians together, then there is a danger of Italy supporting the most restrictive policy, which will undoubtedly be that recommended by the U.K. If, on the other hand, I can persuade the Italians (as I think I can) to accept this present proposal, I may also be able to prevail separately upon the British in the same way.¹⁵

Hampton's proposal stated that, together with the supplementary programme, the Council should approve a document establishing the procedure for its control, including a financial plan with the estimated total cost of the project and annual expenditures for the construction period. This implied that any deviation from the

1965 and its report (CERN/FC/LWP/2, 16/3/65) is annexed to the document CERN/FC/757, 17/3/65. Handwritten minutes of this meeting and a first draft of the final report can be found in file DIRADM 20104.

¹³ Finance Committee, 66th meeting (23/3/65), CERN/FC/766/Draft, 26/4/65.

¹⁴ Council, 29th session (25/3/65), CERN/590.

¹⁵ G.H. Hampton, letter to W. Schulte-Meermann, 6 April 1965, DIRADM 20305. See also Hampton's letter to S. D'Andrea (adviser of the Italian delegation), 5 April 1965, *ibidem*. About the critical role of Britain in advocating the need to limit and control CERN expenditure and in defending lower budget figures ever since 1957, see Krige (1990).

principles listed in the document required fresh consideration by the whole Council and approval by a two-thirds majority while normal budget decisions were to be taken by a simple majority, in accordance with the Convention and with the so-called "Bannier procedure".¹⁶

At the Finance Committee meeting of 3–4 May, 1965, the philosophy of Hampton's proposal was generally accepted – Italy in particular expressed its satisfaction with it – but the U.K. presented an alternative proposal which defined rules for much stricter financial control. Two points were stressed in particular: the first established a link between the basic and the supplementary programme, requiring that the financial plan of both programmes should be approved for the construction period of the ISR; the second aimed at introducing the principle of the so-called two-thirds qualified majority, namely that any budget decision had to be taken by a majority of two-thirds of the Member States representing not less than two-thirds of the total contributions. The British delegate, R.St.J. Walker, went as far as to point out that "the acceptance of two-thirds majorities would be a most important factor in the United Kingdom's decision to participate in the storage rings programme."¹⁷

Just a few weeks before the June Council meeting where the ISR programme was to be finally approved, the British position posed a major problem. Considering that Germany would have approved the ISR programme only on condition that its contribution did not exceed 25 % (the so-called 25 % rule), and that smaller Member States, on the contrary, were unable to approve it if the 25 % rule was enforced because of the resulting financial burden on them, the only possibility to pass the programme was to get the participation of nearly all Member States and in particular all major ones. In this case, as Bannier put it, "The 25 % rule would only have a marginal effect and the Netherlands Delegation [and presumably other smaller Member States' delegations] might then be able to

¹⁶ Hampton's proposal is in CERN/FC/769, 23/4/65, and CERN/586/Draft, undated. The very first draft of this document is appended to Hampton's letter to D'Andrea. The "Bannier procedure" (CERN/442, 29/5/62) was based on the principle of a four-year rolling budget approved each year, namely the budget for the first year, a "firm budget determination" for the second year and a "provisional determination" for the following two. The firm determination could be changed only without dissent in the Council. On this topic, see Krige (1990), p. 604–623.

¹⁷ Finance Committee, 67th meeting (3–4/5/65), CERN/FC/777/Draft, 3/6/65, p. 7. The British document is CERN/FC/773, 3/5/65.

accept it as a matter of fact though not as a matter of law."¹⁸ The menace of the withdrawal of the United Kingdom from the ISR project at this stage could have definitely jeopardized the project itself.

In order to find a solution before the Council meeting, a special working group was set up by the Finance Committee, including Schulte–Meermann, Walker, A. Alline (France), C.E.I.M. Hoogeweegen (Netherlands), and Hampton. The group met in Bad Godesberg on 14 May and the outcome of the meeting was a revision of Hampton's original proposals that Hampton himself was asked to draft. In particular, following one of the British requests, it was decided that the financial plan of the basic programme during the construction period of the ISR should also be included in the document to be approved by the two-thirds majority of the Council as part of the decision of principle to build the ISR.¹⁹

No agreement could be reached, however, on the problem of the voting majority for annual budgets. The U.K. insisted in its proposal of a two-thirds qualified majority both during the construction period and later; in particular, as the Convention established that the budget should be voted by the Council with a simple majority, they suggested that the Council should approve a special instruction to the Finance Committee by which any budget recommended to the Council by the Committee itself had to be supported by a two-thirds qualified majority. The other members of the Working Group, on the contrary, were of the view that "this question called for more thorough examination than was possible before the June Council session, and that this could be done as part of the study which is now being made of a revised convention to take account of the 300 GeV accelerator project."²⁰

The members of the Finance Committee were also confronted by strong reservations from the CERN administration. Considering, in fact, that "the

¹⁸ Committee of Council, 48th meeting (16/6/65), CERN/CC/605/Draft, p. 4. The 25 % rule, namely the proviso that no member state should pay more than 25 % of the costs of a programme, had been explicitly included in the Convention for the basic programme but not for supplementary programmes. According to the report of the Working Party of legal experts, the Council had the possibility to introduce such a rule for a particular supplementary programme such as the ISR programme.

¹⁹ CERN/FC/769/Rev, 24/5/65, and CERN/586/Draft/Rev, undated. See also the correspondence of Hampton with Walker and Schulte–Meermann in file DIRADM 20305.

²⁰ CERN/769/Rev, 24/5/65, p. 1.

document now presented [was] in effect a proposal from Member States rather than from the Administration", Hampton felt obliged to make clear to the Finance Committee and to the Council what the views were "in the house" on the proposal itself.²¹ A severe criticism, in particular, was addressed to the British proposal on the qualified two-thirds majority for approval of annual budgets. The arguments stemmed from long-time experience in financial debates as well as from sound pragmatism:

Experience has shown that it is not easy to reach a recommendation within the Finance Committee about future budget figures, and it seems improbable that this will be made simpler by demanding a larger majority before a recommendation may be made to Council. The most likely result would be that, even more often than at present, a decision would have to be taken in Council, where a simple majority would prevail. There is, moreover, no evidence that in those organizations where qualified majorities exist, decisions are more easily taken or are of better quality. CERN has behind it ten years of successful operation unrivalled in any other organization, and one is tempted to feel that this is due in no small measure to the spirit in which the Council has resolved the differences which have arisen in the past. This has rarely been done by recourse to voting majorities, but rather by a readiness to take full account of the positions of individual Member States. This has perhaps been encouraged by the fact that only a simple majority was normally required for such decisions. The more formalistic approach which is implied by the use of qualified voting, particularly in the proposition that this should be applied in the Finance Committee to normal budgets, may well damage this spirit.²²

On the eve of the Council meeting the situation was at a deadlock and those attending the meetings of the Finance Committee, where the revised document was discussed, and of the Committee of Council, where a further discussion took

²¹ Hampton, letter to Walker, 3 June 1965, DIRADM 20305. The Administration's document is CERN/599, 2/6/65.

²² CERN/599, 2/6/65, p. 3.

place, could only acknowledge it.²³ It was finally decided to submit to the Council a resolution by which it just approved "in principle" the ISR supplementary programme, with no reference to financial control. Member States willing to participate in it were to decide by the time of the December meeting of the Council, when a document fixing the financial plan and the procedures of budget control would also be approved. In the meantime the Finance Committee would continue the discussions and find an agreement on this topic.

Later that same day, at the official session of the Council, Sir Harry Melville declared, to the great relief of all delegations and of CERN management, that he was "happy to announce that Her Majesty's Government has decided in principle that the United Kingdom should participate in the ISR project provided that the project commands general acceptance." The resolution was unanimously approved and the President, while thanking all those who had had a role in this successful outcome, felt obliged "to pay tribute especially to the United Kingdom Delegates, for whom this decision had posed particularly difficult problems."²⁴

The search for a compromise

As a matter of fact, while the ISR programme was now definitely approved "in principle", the legal and financial problems were far from being solved, and the members of the Finance Committee had to confront them again when they met in July to continue the discussion on financial control procedures. The contraposition on the voting procedures arose again as harsh as ever. The British delegate insisted that "the adoption of the principle of the qualified two-thirds majority for the two programmes was of vital importance for the decision his Government would take in December in connection with the storage rings"; the French délégué, on the contrary, objected that "there had never been any question of accepting a two-thirds majority of votes and of contributions as proposed by the United Kingdom."²⁵ He continued arguing that "the objection raised by the French

²³ Finance Committee, 68th meeting (15/6/65), CERN/FC/785/Draft, 7/7/65; Committee of Council, 48th meeting (16/6/65), CERN/CC/605/Draft, 20/8/65.

²⁴ Council, 30th session (16–17 June 1965), CERN/604, p. 24–25.

²⁵ Finance Committee, 69th meeting (12–13/7/65), CERN/FC/790/Draft, 27/8/65, p. 9–10. See also CERN/FC/788, 12/7/65.

Delegation to the United Kingdom proposal was one of principle [because this] proposal was completely at variance with the provisions of the Convention." All other delegations shared this opinion, even though most of them declared that they would eventually accept a simple two-thirds majority, namely a majority of two-thirds of the Member States present and voting, only for the ISR programme. Again, no agreement could be reached.

Just before the following meeting of the Finance Committee, the delegates from the four major countries met to find a last-minute compromise. However, they did not understand each other on the main issue. In fact, at the official meeting, Walker said that a compromise had been agreed by which annual budget figures should be approved in the Finance Committee by a two-thirds simple (not qualified) majority for both programmes. To this the French delegate objected strongly, arguing that agreement had been reached that this procedure would be required only for any departure from the estimates in the supplementary programme.²⁶ The Italian and German delegates supported this statement.

At this point, Hampton reported to Bannier, "the Finance Committee broke up in a certain amount of confusion, because by then no-one was clear who had agreed with what." He went on informing the President of the Council that "the British are completely unable to accept simple majorities in the Finance Committee for the budget decisions and if they are not given more than this, then they will press for an amendement to the Convention with the consequent delays which would then result."²⁷ In fact, the real British worry about budget control was not so much the construction period as the operating period after 1971, when the budget would be running at levels around 300 million Swiss francs per year, namely nearly twice as much as in 1965. On the other hand, on the request of the Chairman of the Finance Committee, the French delegation issued a document explaining the principles which they, as well as the Germans and the Italians, supported.²⁸

It was clear that the Finance Committee was unable to find a solution for what had become a hard political issue and a tough confrontation of rather rigid

²⁶ Finance Committee, 70th meeting (28/9/65), CERN/FC/799/Draft, 27/10/65.

²⁷ G.H. Hampton, letter to J.H. Bannier, 30/9/65, DIRADM 20305.

²⁸ CERN/CC/611, 2/11/65.

positions. It was then decided to arrange the continuation of the discussion after the meeting of the Committee of Council, in order to reach a conclusion following directions from higher political level. Hampton himself kept negotiating informally with the parties involved.²⁹

By the time the Committee of Council met, on November 9th, the British position had been accepted, notwithstanding the fact that all other delegations represented in the Committee would have preferred the method of simple majority.³⁰ In fact, this was somehow an inevitable choice if they wanted to keep the U.K. in the ISR programme. It was agreed, however, that, in case the Finance Committee should eventually be unable to make budget recommendations by the required two-thirds simple majority, it would be up to the Council to reach a final decision in accordance with the provisions of the Convention (i.e. by a simple majority).

The document which laid down the financial plan of the ISR programme and the agreed procedures for its control was finally approved by the Finance Committee, submitted to the Council and eventually approved, together with a resolution requesting the Finance Committee to ensure that any figures for budgets to be recommended to the Council should be supported by a two-thirds majority of Member States represented and voting.³¹ At the same time all CERN Member States bar Greece announced they would participate in the programme and the budget for 1966 was approved, thus giving the green light to the construction of the ISR.

Building the machine

The design study of the ISR had been worked out at the CERN's Accelerator Research Division since 1961 by a special Study Group on New Accelerators led

²⁹ G.H. Hampton, letter to J. Martin, 14/10/65; B. Gregory, letter to Hampton, 15/10/65; J. Martin, letter to Hampton, 19/10/65; DIRADM 20305.

³⁰ Committee of Council, 49th meeting (9/11/65), CERN/CC/623/Draft, 8/12/65.

³¹ Finance Committee, 71st meeting (10/11/65), CERN/FC/816/Draft, 24/11/65; 72nd meeting (25/11/65), CERN/FC/825/Draft, 13/12/65. "Procedure for the establishment and control of a supplementary programme for the construction of Intersecting Storage Rings", CERN/613, 25/11/65. Council, 31st session (15-16/12/65), CERN/634, annex II (also CERN/614).

by K. Johnsen. The final report of this Group, issued in May 1964, formed the basis for the eventual implementation of the project.³² Fig. 4 shows the general layout of the ISR and its association with the CERN Proton Synchrotron (PS), as presented in this report. Three experimental halls were foreseen in the project: two of them, at intersections I-4 and I-5, were for colliding beams experiments; the third, around I-1, was mainly intended to increase and improve the facilities of the PS for experiments with 25 GeV protons. The protons circulating in one of the ISR rings, in fact, could be used up in a target or extracted, much as in the PS, but at a steady controllable rate rather than being tied to the cycle of the accelerator. The same hall would be used for assembly work during the construction period.³³ At all other intersections, facilities (access, floor pit, etc.) were foreseen in order to allow colliding beam experiments in the available width of the tunnel.

The original design did not undergo major modifications during the construction phase. After the approval of the project several discussions took place among physicists about the possibility of head-on or near head-on collisions, and the question was raised whether this could be achieved in the ISR project as proposed. It was then decided to reconsider the question of the crossing angle and, as a consequence, of the entire magnet structure of the ISR. In autumn 1965 the Study Group went into the analysis of this problem and concluded that no structure with a crossing angle smaller than 9° was practicable.³⁴ Both in this case and in the original 15° crossing, strong magnetic fields over a long distance were needed in order to reach 0° collisions in good experimental conditions, which would have been feasible with superconducting magnets if significant progress had been realized in this field. While the 9° structure required a weaker magnetic field and had in fact certain technical advantages, it was more expensive and caused a significant reduction in flexibility from the experimental point of view, in particular because it reduced the space available for experimental apparatus in the region between the two rings. Following further discussions with physicists, it was recognised that there was no strong clear-cut argument in either

³² ISR (1964).

³³ Hine (1964).

³⁴ Johnsen et al. (1965).

direction, but that altogether the original 15° structure had been studied best and thus it was to be preferred.

While the structure of the rings remained essentially unmodified, two significant changes in the general layout of the ISR were decided at an early stage of the project development, following discussions between the constructors of the machine and future users.³⁵ The first one was the moving of the 25 GeV experimental hall to the opposite side of the rings. In the original position, in fact, a proton beam could be transferred from the PS to this hall only *via* the ISR, with the great disadvantage that no beams of any kind could be sent to the hall while installation or maintenance work took place in the ISR tunnel or while colliding beam experiments were being performed in the machine. This significant limitation in the time available to potential users would have seriously reduced the usefulness of the hall. In the new layout, protons from the PS and from the ISR reached the hall, later known as "West Hall", by separate and independent channels and the gain in running time largely surpassed the slight disadvantage that this configuration did not allow the mode of operation with internal targets. The West Hall was completed in 1968 and during the construction of the ISR it was used by the ISR Division for assembling and testing the various components of the machine.

The second change regarded the colliding beam experimental halls. As we have seen, only two had been envisaged (at intersections I-4 and I-5), a choice motivated by economic reasons as well as by prudence due to lack of experience about colliding beam experiments. Both these halls were buried under heavy earth shielding, thus making any material modifications difficult and time-consuming. Moreover, these halls were very similar in character, being well suitable for detection of particles emerging close to the magnets of the machine. On the contrary, they did not offer the possibility of moving far from the interaction region, as required for time-of-flight experiments, particularly at large angles. The interest in having two experimental halls with different characteristics and greater flexibility was stressed by the physicists in their discussions with the ISR builders and so it was suggested to suppress hall I-5 and to construct a colliding beam hall at intersection I-1, in place of the original 25 GeV hall. Due to the

³⁵ Johnsen & Van Hove (1966), in particular Appendices III and IV.

topography of the site at I-1, it was possible to provide free access to the hall from both sides of the ring and a considerable amount of flat open space.³⁶ Fig. 5 shows the agreed final layout of the ISR.

According to Johnsen, from the very beginning the ISR project leader, "the ISR construction proceeded fairly uneventfully, although those involved experienced considerable anxiety at times."³⁷ As a matter of fact, because of the novelty and the complexity of the design of the new machine, the people involved in the construction were well aware that it was "a daring and bold project", which required tight tolerances and the highest performance for all components. The reorganization of the structure of CERN at the beginning of 1966, approved by the Council after a proposal of the new Director General B. Gregory, helped to provide an institutional context particularly suitable for the successful realization of the project.³⁸ In the new framework, in fact, an ISR Construction Department was created, which gave its director Johnsen a place in the CERN Board of Directors. Johnsen was also leader of the new ISR Division, which was independent from the Accelerator Research Division.³⁹ The ISR Division was also responsible for the technical study of the 300 GeV accelerator because of the important part played in both projects by some of the key personnel in it. When the division was created, on 1 January 1966, it consisted of 88 staff; this figure increased to 162 by the end of the year and kept rising during the construction period (table 3).

Responsibility in CERN top management, institutional autonomy within CERN organization, and financial autonomy as a supplementary programme, were all factors which significantly contributed to the smooth implementation of the ISR project. This, in particular, was completed within the budget and the construction of the rings was completed four months ahead of schedule, certainly a remarkable achievement in the field of high technology devices in international

³⁶ Johnsen & Van Hove (1966). Discussions with physicists are reported in "Minutes of discussion on ISR experimental areas and buildings, 18 March 1966", 24/4/66, and "Notes on discussions of the ISR Working Party", 11/5/66; NP 22897.

³⁷ Johnsen (1984), p. 4; Johnsen (1986), p. 168.

³⁸ See chapter X in this volume.

³⁹ The Accelerator Research Division remained not incorporated in any department while the ISR Division was in fact the only division of the ISR Construction Department and practically coincided with it.

organizations (tables 4 and 5). In order to understand the excellent performance of the ISR Construction Department one must consider two other important aspects. The first is that the project had been carefully studied for several years and eventually implemented by an already experienced team - most of the people, in fact, had been involved in the construction of the proton synchrotron. The second is that, while formally engaged in an independent, supplementary programme, nevertheless they could largely avail themselves of the facilities and technical expertise already established at CERN. It is significant, in this respect, that most savings were realized in the magnet system, where these two aspects could play a major role.

Johnsen organized his department on the basis of the experience gained in the construction of the PS. Working groups were created with responsibility for the different components of the machine (table 6). The group leaders (the "Parameter Committee") met regularly on Mondays and the system worked as a "guided democracy", according to Johnsen's *a posteriori* recollections.⁴⁰ An important aspect of the construction of the ISR was that, due to the high sophistication of the design and the strict requirements on the components, all project development was made inhouse, every part of the machine was carefully designed and tested at CERN while industries received given final blueprints with very tight tolerances. In 1969 a special Beam-Equipment Interaction Committee was created to monitor at the design and prototype stage all components that could interfere with the beams. According to Johnsen, "this was a difficult task but an extremely important one [and] this foresight avoided much potential trouble."⁴¹

In the following sections I will review the most significant aspects of the construction and commissioning of the ISR.

General layout and engineering

Three groups (Survey, General layout, and Technical engineering) took care of all complex problems related to the civil engineering work on the site, the definition of the general layout of the machine and its facilities and the correct installation of technical systems. Invitations for tenders on the main civil

⁴⁰ Interview with A. Russo and J. Krige, 30/8/90 - 1/9/90.

⁴¹ Johnsen (1984), p. 5; Johnsen (1986), p. 169.

engineering work were sent to about 30 firms in the Member States in October 1965 and, after a long phase of negotiations, a contract was signed in September 1966 and the contractor started excavation work on the site. Work on the 10,000 m² West Hall started in May, the following year.

The construction of the circular tunnel where the ISR rings were to be housed resulted in a very complex enterprise because of the special geometry of the machine and of its requirements. The tunnel, in fact, was much wider (15 m) than that of a standard accelerator because it had to contain two rings which, in the centre of each octant, were as distant as about 9 m. Moreover, it had to house many facilities and devices such as injection and ejection systems, experimental halls, etc. Finally, one must recall the severe requirements on shielding against radiation background in a machine characterized by high energy and intensity of the beams. The ring building was closed in November 1969; by that time the beam transfer tunnels had been completed as well as all construction accessory to the machine and the installation of machine components was already in progress.

An important aspect of the construction of the ISR, dealt with by J. Gervaise's Survey Group, was that of the proper linking up of the rings with the PS and the correct positioning of the magnet system in order to provide the very precise field configuration required to guide and focus the beams along the 4 Km of tunnelling in the booster, the PS, the transfer tunnels and the two rings of the ISR.⁴² The expression "accelerator metrology" was used at CERN to indicate this kind of activity.

An accurate triangulation was made of the whole site which assured the self-consistency of the coordinates of the markers within ± 1.5 mm throughout the entire perimeter of the ring. For this a special, automatic measuring device (*distinvar*) was developed, capable of assuring an accuracy of 14.7μ over a distance of 50 m.⁴³ Its data were then checked by a special instrument for the optical measurement of distances (*mekometer*) originally designed and developed at the National Physical Laboratory, Teddington, U.K., a prototype of which was built at CERN and was ready to be used by May 1969. Unfortunately, on the 16th

⁴² Gervaise (1970a) and (1970b).

⁴³ The *distinvar* is a measuring device based on the accurate length measurement of an invar wire stretched between two points. The model developed and used at CERN is described in Gervaise (1965).

of that month, the Metrology Group's specialist for the electronics of the CERN mekometer was killed in a helicopter crash. As it was impossible to readjust the CERN instrument, two specialists from Teddington were invited to come and make the planned measurement, which they did, however, rather unsatisfactorily due to haste.

The positioning of the magnets and other scientific equipment within the framework provided by the triangulation required a much more refined accuracy as some 2000 components had to be positioned in relation to each other with an accuracy in the order of a tenth of a millimetre. This was achieved by a careful positioning of the magnets with respect to a reference figure made of a double row of 64 survey monuments along the ISR tunnel. By the end of 1970, when the magnets were all in place, measurements of the radial deviation between the measured value of the orbit and the theoretical value was as low as ± 0.02 mm for magnets close to a pair of monuments and ± 0.06 mm for magnets in the centre of the reference figure. A similar measurement of the vertical deviation gave, on ring 1, a value of ± 0.07 mm.⁴⁴

The magnet

The aim of the main magnet system of the ISR, as in any strong-focusing, alternating-gradient synchrotron, was to keep the high energy protons on the exact radii of curvature and to provide an alternating focusing and defocusing force (resulting in a net focusing gain) on the beams. In the case of the ISR, however, much stricter requirements were imposed on the stability and correct position of the orbit. Focusing (F) and defocusing (D) bending magnet units were arranged along the circular vacuum chamber together with compensating magnets such as skew quadrupoles (to prevent coupling of radial and vertical oscillations), Terwilliger quadrupoles (to focus protons of different energies at four of the intersection regions in order to reduce the beam cross section and increase luminosity), sextupole lenses (to compensate the restoring forces so that protons of different momenta have the same betatron frequency), and radial field magnets (to steer the beams in the vertical plane in the intersection areas).

⁴⁴ CERN, *Annual Report*, 1970, p. 108–109.

A great deal of flexibility had been designed in the magnet structure in order to allow fine adjustments and to correct orbit distortions. In particular, pole-face windings with 12 independent circuits were provided on each magnet unit and a good number of them had also auxiliary windings placed between the main coils and could be moved up and down by remotely controlled screw jacks. In each ring there were a total of 68 focusing and 64 defocusing units, 28 skew quadrupoles, 48 Terwilliger quadrupoles, 16 sextupoles, and 20 correcting radial field magnets. Finally, the beam transfer between the PS and the ISR constituted another large magnet system consisting of bending and focusing magnet units, with special septum magnets and fast kicker magnets at injection points.

In the magnet system too, allowed tolerances were extremely tight. The magnet field could not vary by more than 5×10^{-4} from unit to unit and then the mechanical tolerance on the profiling of the magnet pole faces was therefore 0.01 mm. The magnet units had to be put in the right place to a precision of about 0.2 mm horizontally and 0.1 mm vertically. The power supply had to have a long-term stability of 10^{-4} with a short term stability of 3×10^{-5} . These accuracies were achieved, commented Johnsen with a sense of pride that can be understood.⁴⁵

As early as 1964 a first magnet model was ordered and magnetic measuring techniques were developed by Johnsen's group; measurements with this model started in the fall of the following year. In the same period extensive investigations were pursued for the choice of steel for the magnet cores. By August 1966 the Magnet Group sent detailed specifications to 38 steel firms, twelve of which gave preliminary positive answers, and then started technical discussions with prospective manufacturers. The specifications of the cores and the invitations to tender were issued by the end of that year and all main components of the magnet system were ordered during 1967.⁴⁶ In the summer of 1968 the first elements of the series production of the magnet system started to arrive at CERN and the Magnet Group staff moved into the new West Hall to assemble and test all magnet units before installation in the ring tunnel. The systematic, careful measuring programme was made possible by two precision benches of black diabase equipped with probes and electronic readout and by the

⁴⁵ Johnsen (1973), p. 212-213.

⁴⁶ CERN, *Annual Report*, 1966, p. 116; 1967, p. 121.

use of an on-line computer for the immediate reduction of magnetic measurements. Special vehicles were designed and built for the transport of the different units in the ring tunnel and in the beam transport lines.

Assembly and measurements of the main magnet units were finished in March 1970 and in May all 264 units were installed in the ring tunnel. By the middle of the same year, all auxiliary magnets had been delivered and measured and their installation and cabling proceeded together with the installation of the corresponding vacuum elements. The system was provided with a specially designed "field-display system" for monitoring magnetic fields and gradient during operation. The result of the Magnet Group's work, after the commissioning of the machine, was summarised in a few lines of the CERN *Annual Report* for 1971:

All magnets have performed without failure, no change in magnetic behaviour has appeared, and the influence on the proton beams corresponds well with forecasts based on previous magnetic measurements. The field display system has proved reliable and accurate, and is regularly used as a reference to define central momentum and for setting the excitation of the main magnets and their auxiliary windings.⁴⁷

The vacuum system

It was clear from the very beginning that the vacuum problems were "of the most severe technological ones [to be expected] in the construction of the ISR."⁴⁸ In fact, proton scattering in the residual gas affected the performance of the ISR in two aspects: the lifetime of the circulating beams and the interaction rate in colliding beam experiments. It had been calculated that an average pressure of 10^{-9} torr was required along the whole length of the vacuum chamber while a still lower pressure, less than 10^{-10} torr or even 10^{-11} torr, was required in the colliding beam areas where one wanted to observe scattered protons.⁴⁹ As a comparison,

⁴⁷ CERN, *Annual Report*, 1971, p. 107.

⁴⁸ Johnsen (1965), p.4.

⁴⁹ ISR (1964), p. 136 ff.

one can consider that in conventional accelerators, pressures around 10^{-6} torr were considered adequate and that values less than 10^{-9} torr were feasible only in small bench-models by the time the ISR was designed. In this case the total length of the vacuum vessel in the two rings was almost 2 km with thousands of joints. In fact, the ISR was to be by far the biggest ultra-high vacuum system in the world.⁵⁰

For the design of the vacuum chamber and of the pumping system, the ISR people could avail themselves of the experience gained with the CERN Electron Storage and Accumulation Ring (CESAR), a machine which had been designed and built in the early 1960s to study experimentally some of the basic problems of the proton storage rings.⁵¹ The design pressure of CESAR was 10^{-9} torr: in fact it succeeded in achieving a working pressure of 5×10^{-10} torr for most of its life, up to a mean pressure of 7×10^{-11} torr in its final phase (June–December 1967).

Three aspects were to be considered for the proper management of the vacuum problem: the structure of the vacuum chamber, the baking process, the pumping system. The vacuum chamber of each ring of the ISR was composed of many sections of different type, joined by more than 6000 demountable flange seals with bellows and metal gaskets.⁵² One type of chamber section was that included in the magnet gaps: it had an oval cross section of internal dimensions 160x52 mm and 2.3 mm wall thickness. A normal chamber for straight sections was cylindrical with a diameter of 160 mm and a wall thickness of 1.5 mm. Special wide chambers were also provided in straight sections at RF acceleration stations, pick-up stations, and so on. All these chamber sections were made from seam welded, high temperature (1000 °C) vacuum annealed stainless steel sheet with low magnetic permeability ($\mu \leq 1.004$) and low desorption rate. All parts of the system were designed and tested to resist the baking temperature up to 300 °C.

In order to allow the separation of one given sector of the system for repair or modification without exposing the whole chamber to atmospheric pressure, a set of special sector valves was foreseen between the 8 outer arcs, the 8 inner arcs and the 8 interaction regions. These valves had to be capable of withstanding baking at

⁵⁰ Fischer (1971).

⁵¹ CESAR (1968).

⁵² Samuel (1970).

high temperature in both the open and closed states and so tight that either of the two rings could be operated with ultrahigh vacuum while the other one was partly or wholly exposed to air. Such valves did not exist on the market and in fact they were at the limit of what was technologically possible. Their development resulted in one of the most difficult aspects of the whole vacuum system.⁵³

All parts of the vacuum chamber were degassed by heating at about 250 to 300 °C in a helium tank for 2 hours and then, after installation in the rings, there was a final bake-out under vacuum at 300 °C for 24 hours. This, in fact, was the procedure as originally foreseen. During the construction period new bake-out procedures, which seemed satisfactory in laboratory tests, were tried in order to limit the duration of a shut-down of the machine involving the vacuum system.⁵⁴ The method adopted consisted in baking-out at 200 °C for 5 hours. The first year of operation of the ISR revealed, however, that the circulating beam led to drastic pressure increases, which in turn limited the maximum current that could be stored. It was understood that the beam created ions from ionization of the residual gas; these ions bombarded the chamber walls liberating gas molecules which were a further source of ions. As a consequence of this avalanche phenomenon, a "pressure bump" was created once a certain current level was exceeded.⁵⁵ It was then decided to go back to the original baking-out procedure as well as to improve the surface treatment for critical chamber sections before installation by glow-discharge cleaning. Moreover, more pumping capacity was added in the form of hundreds of titanium sublimation pumps all around the rings.⁵⁶ On this occasion the great flexibility embedded in the ISR design proved decisive: in fact, the addition of these powerful additional vacuum pumps was possible because the vacuum vessel was accessible, particularly in the sideways open long bending magnets. Without this unforeseen facility the circulating beam intensity would have been limited to very modest values (≈ 1 A) giving in turn totally unsatisfactory luminosities for the physics experiments.⁵⁷

⁵³ ISR (1969); CERN, *Annual Report*, 1969, p. 115.

⁵⁴ CERN, *Annual Report*, 1969, p. 115.

⁵⁵ The phenomenon was first reported by K. Johnsen at the 64th SPC meeting of 11 May 1971, CERN/SPC/307/Draft, 30/7/71, p. 20–22.

⁵⁶ CERN, *Annual Reports*, 1971, p. 104–106; 1972, p. 111; 1973, p. 109–110.

⁵⁷ I wish to thank F.A. Ferger for bringing my attention to this aspect.

The pumping system of the ISR was in three stages. The first one, designed to rough down the system to 10^{-6} torr, consisted of 35 turbomolecular pumping stations per ring. The pressure was then taken down to about 10^{-10} torr by 144 sputter-ions pumps per ring. The third stage included titanium sublimation pumps at critical places: at the beginning of operation they were 34 around either ring; they later became about 500 in the whole system. As a result of all efforts to improve the vacuum system, an average pressure value as low as 1.5×10^{-11} torr was achieved in the first period of operation while, in the course of following years, average pressures of almost one order of magnitude lower were attained, with values as low as 10^{-13} Torr in experimental areas (fig. 6).

The RF system and the stacking process

The purpose of the radio frequency (RF) system of the ISR was to pick up the bunches of protons arriving from the PS, to accelerate them from the injection orbit to the stacking orbit, and to deposit them there without affecting the existing ribbon of stacked protons. This process had to be synchronised in such a way that the frequency of the accelerating field was in tune with the arrival frequency of incoming bunches of particles and out of tune with the circulating frequency of the stored particles. Thanks to a phase-lock system, the bunches of protons from the PS were trapped in the RF "bucket of stability" in phase space and moved bodily across the tube to the stacked ribbon. The radio-frequency system, designed to achieve this process of acceleration and stacking, consisted of 7 accelerating cavities in each ring, arranged in two groups of four and three units respectively, with a centre frequency of 9.55 MHz (i.e. the frequency of the PS at maximum energy) and capable of delivering accelerating voltages from about 20 kV down to 50 V.

Apart from the usual highly sophisticated technical development, the main improvement in the RF system during the construction of the ISR came from a theoretical suggestion, the so-called "stacking with missing buckets" scheme, originally proposed by W. Schnell after a suggestion of A. Schoch.⁵⁸ The starting point is to consider that a pulse from the PS normally consists of 20 bunches and

⁵⁸ Schnell (1966) and (1967). See also Ruggiero (1968).

that the circumference of the ISR is $3/2$ times that of the PS. As the frequency of the two machine must be the same it follows that there are 30 buckets in the ISR, only 20 of which are occupied by a train of bunches. In other words, a pulse from the PS would fill only $2/3$ of one ISR ring. Therefore, during each stacking cycle, the 10 empty buckets would enter the ribbon of stacked particles as a sort of "beam hole" in the phase space, causing a dilution of the beam intensity. In order to overcome this limitation in the stacking efficiency the RF system was designed so as to chop the signal following the passage of the last bunch in a pulse until the arrival of the first bunch of the next pulse.

Among the tasks of the RF Group there was the realization of highly sophisticated diagnostic equipment to control the stacking process and the quality of the beams. More than a hundred stations for beam position monitoring were installed around the vacuum chamber, coupled with a video system for displaying information on oscilloscopes. Orbit distortions of about 0.1 mm could be detected.

Controls

The Controls Group was established by the middle of 1966 and it soon devoted particular attention to the possible application of an on-line process computer for the machine control system. This sounds obvious today but it was, in fact, a matter of research and development in the mid-1960s. The Group also had responsibility over the development of the beam dump system and over the personnel protection system.

At the end of 1970, when the installation of most of the control and other signal transmission cables was finished, the total length of installed cable was nearly 1000 km and more than 20,000 individual cables and over half a million individual connections had been made.⁵⁹ Among the various aspects of the control of the machine performance, special attention was paid to the remote control of the magnet units, to the monitoring of the vacuum system, and to the monitoring of the beam quality. The control system set up for the ISR enabled the operators in the control room to use computer terminals to record and adjust the currents of

⁵⁹ CERN, *Annual Report*, 1970, p. 108.

about 300 magnet power supplies as well as to adjust the vertical position of individual magnet units to a precision of 1/100 mm.⁶⁰

As to the control equipment for the vacuum system, 300 ionization gauge control units were ordered in 1968 as well as 325 power supplies for the sputter-ion pumps. The following year a system to control the turbomolecular pumping system was designed and tested and an order was placed to manufacture 80 complete systems. Finally, in 1970, 120 sublimation pump control units were purchased. The monitoring of the temperature of all parts of the vacuum chamber during the bake-out of one sector was provided by four scanning systems.

We have already dealt with the particular attention devoted to the development of the most sophisticated beam diagnostic equipment. In fact, all information about the quality of the beam was available on-line in the ISR control room. In particular, the beam monitoring system, for both the beam-transfer system and the storage rings, included 23 luminescent-screen monitors, 10 of which were observed via radiation-resistant TV cameras, and 16 secondary-emission monitors for measuring beam phase-space ellipses. The pulsed beam current in the beam-transfer system and at injection could be monitored and read out in the control room at an accuracy of better than 1 % while a special d.c. current monitor measured the circulating beam in the storage rings in the range from about 100 μ A to 20 A, with the current values displayed on digital voltmeters or plotted on a paper recorder.

The beam diagnostics system continued to be improved after the commissioning of the ISR and, in the words of Johnsen, "this development belonged to the most exciting experiences at the ISR."⁶¹ The most important result in this field was the use of the so-called "Schottky noise" as an element in beam diagnostics. This phenomenon consists in the statistical fluctuations in the beam current and beam centre of gravity due to the finite number of circulating protons. These fluctuations are very small and had not been observed in accelerator beams before they were observed in the ISR in 1972. The Schottky noise soon became

⁶⁰ Johnsen (1973); CERN, *Annual Report*, 1969, p. 116.

⁶¹ Johnsen (1984), p. 14; Johnsen (1986), p. 177.

extremely important not only as a tool for diagnostics in the ISR and other colliders but also for the practical development of stochastic cooling.⁶²

Running-in

On 29 October 1970, the ISR team was ready to inject the first protons into one of the rings. Here is how Johnsen summarized the event to CERN's Scientific Policy Committee:

At 8.00 p.m., when the test was due to start, all was in readiness. [...]

At 8.32, with all stops taken out, a pulse from the PS was sent along the beam-transfer line and injected into Ring 1. It circulated at once and stayed in the ring until kicked out by the dumping system. Before any adjustments were made, the first lifetime test took place between 8.58 and 9.19 p.m. The dumping was stopped and the pulse allowed to circulate for 21 minutes. During this time, the total loss was 22 % and only 0.5 % per minute at the end of the test. The average pressure around the ring was about 3×10^{-9} Torr, nitrogen equivalent. [...] At 11.00 p.m., rather ahead of the planned schedule, came the turn of the RF group. After a few adjustments, but with no attempts of proper tuning, the beam was captured at once. Then the pulses were accelerated across the aperture. Although no plans had been made for doing any stacking of the pulses, it was decided at 00.28 on 30 October to attempt this and the first stack of 55 mA was obtained. [...]

At 2.00 a.m. (the end of the run), another lifetime test was made with intermediate current, only 80 mA (one 20-bunch pulse), and it was found that the beam loss was less rapid than at the higher intensity. [...] During this first test, every component of the ISR had been in use, everybody in the ISR Division had been involved and so all had good cause to feel pleased with the results.⁶³

⁶² Van der Meer (1972), Schnell (1972). It is well known that the technique of stochastic cooling developed by Van der Meer was essential for the realization of the pp⁻ collider at the CERN SPS. For this contribution Van der Meer shared with C. Rubbia the Nobel Prize in 1984.

⁶³ Scientific Policy Committee, 61st meeting (10/11/70), CERN/SPC/298/Draft, 1/2/71, p. 10-11. The event is vividly described in *CERN Courier*, 10:11 (November 1970), 344-347.

An applause burst out at the end of Johnsen's report and the acting chairman of the SPC, F. Perrin, expressed his hope that "full intensity would soon be reached as it would be most important for ISR physicists to start before the Batavia accelerator operated at 500 GeV."⁶⁴

The test runs were resumed in January 1971 and Ring 2 also went into operation. On 27 January, beams at momenta of 15 GeV/c were stacked in both rings with no measurable loss and two successive runs were made, the first one with 4 bunches, the second with the full PS intensity of 20 bunches. For these runs, two teams of physicists had set up counter telescopes at crossing points I-4 and I-5 and, "happy as children on Christmas day", announced that colliding beam events were observed.⁶⁵ At beam-energy of 15 GeV in the rings, the equivalent accelerator energy was close to 500 GeV: Johnsen could proudly announce to the SPC that "the main conclusion of the day was that the ISR can provide an effective facility for research at the highest centre-of mass energies available anywhere in the world."⁶⁶

While rightly satisfied with the successful start of their machine, the builders of the ISR had also to confront the first technical problems. In particular, during the very early operation of the accelerator, it was observed that when they tried to stack beam currents higher than about 3 A, instabilities occurred that resulted in beam losses. Johnsen called this phenomenon the "Brick Wall".⁶⁷ This came as a surprise because this kind of instability, associated with large coherent transverse oscillations, had been considered and a sextupole field component had been built into the magnet profile to avoid it up to much higher currents than 3 A. In the event, it was recognized that the stability requirement was violated in parts of the beam while holding for the global beam on average. It required a great deal of theoretical work and extreme accuracy and flexibility of the components involved

⁶⁴ Scientific Policy Committee, 61st meeting (10/11/70), CERN/SPC/298/Draft, 1/2/71, p. 15.

⁶⁵ "Premières collisions de faisceaux", *CERN Courier*, 11:2 (February 1971), 32-36, p. 34. The technical report of the event, signed by W.C. Middeldkoop and B. de Raad, is *ISR running-in, runs 15 and 16. First observation of colliding beams events*, ISR-BT/BdeR/EEK, 3/2/71, ISR Archive.

⁶⁶ Johnsen's report at the 62nd meeting of the SPC (9-10/2/71), CERN/SPC/303/Draft, 8/3/71, p. 5.

⁶⁷ The term was used for the first time in a report on the start of ISR operation to the CERN Directorate. Johnsen also reported on it at the 62nd meeting of the SPC. See also Johnsen (1984), p. 6-7; Johnsen (1986), p. 170-171.

to compensate the effect and to incorporate a proper feedback system in the machine. In fact, this development went on over many years and led to a gradual increase of the stability limit to around 60 A. The highest stacked current ever seen in a single beam was 57 A, while normal currents during high-luminosity runs were 30 to 40 A. As a consequence the maximum luminosity of the machine kept rising over the years, reaching the value of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, almost two orders of magnitudes higher than the design value (fig. 7).⁶⁸

After further tests with increasing beam energies, the first pilot run, under conditions suitable for colliding beam physics, was successfully carried out during the night of 24-25 February, when beams of about 700 mA were left circulating in each ring for 6 hours:

At the end of this time, the loss had been 1 mA in one ring and 11 mA in the other, and it had been proved that the ISR was ready to receive the first experimental teams on the floor. Consequently, [...] 1st March was taken as the end of the construction period.⁶⁹

The ISR was ready to be used by physicists and they were in fact actively using it when the machine was officially inaugurated, on October 16th, 1971. As V.F. Weisskopf said on that occasion, quoting I.I. Rabi, "The ISR does not ask question of nature; it grabs nature by [the] throat and forces her to speak."⁷⁰

Setting up the physics program

Even though limited to proton-proton collisions, the new machine opened up for experimentation a new and wide range of energies, until then accessible only with cosmic ray experiments. On the other hand, the non-conventional design of the ISR and the novelty of doing physics with colliding beams represented a technical challenge for European physicists.

⁶⁸ Such high values of the luminosity were achieved thanks also to the insertion of superconducting low-B sections which greatly reduced the vertical dimension of the beams, Johnsen (1984) and (1986).

⁶⁹ Johnsen (1973), p. 214-215.

⁷⁰ *Inauguration of the Intersecting Storage Rings, 16.10.1971*, CERN, 1971, p. 7.

Early in 1968 a special Working Party was set up within the ISR Department to discuss the problems involved in experimenting with the new machine. The aim of the Working Party was to help to define an experimental programme for the first period of ISR operation and to design a large, general purpose magnet system for one of the intersecting regions. Regular meetings with CERN physicists were organized by E. Picasso and K. Winter, attended on average by about 40 people, where both the characteristics of the ISR and possible physics experiments were presented and widely discussed.⁷¹ In June 1968, when the ISR project was approaching the mid-point of the construction period, an ISR Users' Meeting was called which was attended by about 300 scientists and represented the first occasion when proposals for experiments with the ISR were publicly discussed.⁷² Four broad areas of investigation were identified for the first phase of operation, namely total cross section, elastic scattering, diffractive and exchange processes, particle production.⁷³

After the meeting many groups from outside CERN expressed their interest in participating in the experimental programme at the ISR and by the end of October the ISR coordination group had been contacted by experimental teams from 21 European laboratories: ten from the United Kingdom, three from Sweden, two each from Germany and Italy, and one each from France, The Netherlands, Denmark, Norway.⁷⁴

Organization and management of the ISR experimental programme

Around that time a lively debate arose inside the CERN Directorate about the kind of organization to set up for the management of the ISR and the definition of its experimental programme.⁷⁵ On the one hand, G. Cocconi, then leader of the

⁷¹ Agenda and summaries of these meetings can be found in file DIRADM 20307.

⁷² The meeting was held on 10–11 June 1968; its programme is in file NP 22898.

⁷³ Minten (1969).

⁷⁴ E. Picasso and K. Winter, circular letter calling for the second ISR users' meeting, 21 Oct. 1968, DIRADM 20306.

⁷⁵ This presentation is based on reports of meetings of the Board of Directors of 17/9/68, 17/10/68 and 22/10/68 and on two *memoranda*, respectively by K. Johnsen and C. Peyrou, both dated 23/10/1968. These documents are in files DGR 21355 and DG 20864. Johnsen's and Peyrou's *memoranda* are also in file DIRADM 20306.

Physics I Department, had suggested creating a strong autonomous group of people, working almost full time on the ISR, attached to the Physics I Department. The role of this group was to design and build general facilities for the experimental areas, to conceive and perform experiments at the ISR and to study experiment proposals from outside in order to assess their feasibility and submit them to the approval of CERN's Nuclear Physics Research Committee (NPRC). Cocconi's proposal reflected the main role that experiments with electronic detectors (the domain of the Physics I Department) were expected to have at the ISR as well as the desire of CERN physicists to keep control over the new facility. At the Board of Directors, Cocconi himself wanted to stress "the difficulty of finding space for visitors on the ISR experimental programme."⁷⁶

An alternative proposal was advanced by the leaders of two other departments, C. Peyrou, leader of the Physics II Department (dealing with bubble chamber experiments), and M.G.N. Hine, leader of the Applied Physics Department. In their opinion, "proposal and preparation of specific experiments should be left open to the free market for groups of physicists of Physics I and Physics II and outside, as is done for the PS."⁷⁷ The discussion and selection of proposed experiments had to be the task of a Committee made up of physicists from both physics departments as well as from outside CERN. Finally, the preparation of large general purpose experimental equipment and facilities had to be left to a group of the ISR Department, possibly assisted by a working party of physicists interested or involved in ISR experimentation. Peyrou also stressed the potential interest of bubble chamber physicists in the ISR and therefore the need to encourage them "to do that sort of physics [in order to] make of the ISR a less restricted gadget than they appeared at the beginning". He then concluded:

If I am completely wrong in my prediction and my optimism and if physics at the ISR is better done by some happy few grouped in a strong group or in a small division, then we better attach it, right away, to the ISR Department.

⁷⁶ Board of Directors, meeting of 17/9/68, CERN/DIR/410, 24/9/68.

⁷⁷ Peyrou's memorandum, p. 2

The difference of opinions echoed the problems and difficulties encountered a few years before in the organization of the experimental work around the PS and reflected the contradictory relations between CERN's physicists and visitors.⁷⁸

Peyrou and Hine's proposal was eventually accepted. By the time of the second Users' Meeting, on 2 and 3 December 1968, it had been decided to leave to the ISR Department the responsibility for building experimental facilities at the ISR and for preparing the approved experiments in collaboration with the experimental groups, and to create an ISR Experimental Committee (ISRC) with the task of examining experimental proposal for the ISR and recommending a coherent experimental programme to the NPRC.⁷⁹ W. Jentschke, then at DESY, Hamburg, was chosen as the chairman of the Committee, which included 5 members from outside experimental groups, 4 members from CERN experimental groups and 3 (later 4) members from the ISR Construction Department.⁸⁰

This decision was probably suggested by a few considerations deriving from the peculiarity of the ISR: firstly, any large experimental facility would interfere with the machine operation and would require proper coupling with its components; secondly, the successful running of experiments depended critically on the correct performance of the machine and on the fine adjustment of all its parameters; finally, after the commissioning of the ISR, a continuous research activity on "machine development" would be required in order to deal with the problems of such a new device and to improve its performance. This set of considerations obviously suggested to keep the management of the ISR and the control of the experimental activity within the organization of the ISR Department.

⁷⁸ Pestre (1990 a). For the relations between CERN physicists and external users, see chapter 12, by J. Krige, in this volume.

⁷⁹ CERN/ISRC/69-1, 15/1/69. This was originally a circular letter by W. Jentschke (first chairman of the ISRC), a copy of which can be found in files NP 22898 and NP 22907. See also B.P. Gregory's letter to G. Cocconi (and other appointed members of the ISRC), 18 Dec. 1969, NP 22899.

⁸⁰ The initial membership of the Committee included W. Jentschke (DESY, Hamburg), F.F. Heymann (University College, London), C. Franzinetti (University of Turin), P. Marin (Laboratoire de l'Accélérateur Linéaire, Orsay), E. Lillethun (University of Bergen), G. Cocconi, G. Charpak, K. Winter (CERN, Physics I Dept.), B. French (CERN, Physics II Dept.), M.H. Blewett (from April 1969), F. Bonaudi, K. Johnsen, L. Resegotti, (CERN, ISR Dept.).

A further consideration called upon the already established CERN practice in the definition of the experimental programmes. In fact, two committees already existed, the Track Chamber Experiments Committee (TCC) and the Electronic Experiments Committee (ECC), devoted to the study and selection of experiment proposals with bubble chambers and electronic techniques respectively. They reported to the NPRC which had the overall responsibility for decisions on CERN's research programme. All three of these committees included members from both inside and outside CERN and, while the chairman of the NPRC was CERN's Director General, the chairmen of the other two were always eminent outside physicists. Thus the choice eventually made for the ISR fitted into an already tried framework on the delicate ground of decision-making procedures for research programmes. However, unlike the two other committees, the ISR Committee was based on a machine rather than on a detector system. In this respect, the ISR was opening a distinct new tradition of research management in particle physics, based on the use of colliding beam accelerators.

Following the example of the EEC, the ISR Committee held both open and restricted meetings. The former were devoted to the presentation and discussion of experiment proposals and progress reports on the programme; in the restricted meetings, the Committee decided about its recommendations to the NPRC.

At the ISR Committee's first meeting, on 13 January 1969, it was decided to call for experiment proposals to be arranged in the four intersections made available for physics experiments during the initial period of operation (I-1, I-2, I-4, I-6). By November, about 30 proposals had been studied and revised and the Committee was in a position to make recommendations to the NPRC for experiments to be distributed at intersections 1, 2, 6.⁸¹ Intersection 4 was reserved for a large magnetic analysis system, the so called *Split-Field Magnet*, whose construction was to start soon and that we will discuss later.

⁸¹ Scientific Policy Committee, 56th meeting, CERN/SPC/284/Draft, 22/1/70. The figure of 30 proposals for experiments was quoted there by the Director-General on behalf of Jentschke, who was unable to attend the meeting, and probably includes also informally presented proposals. As a matter of fact, only 19 formal proposals had been received and filed by the ISRC in 1969. This is also the figure quoted by K. Potter in his *Memorandum* on ISRC statistics prepared on 8 June 1979: Potter's files, folder "Summary of proposals. ISRC statistics".

The definition of the first experimental programme

The definition of an experimental program at the ISR was not just a matter of choice between different proposals coming from several laboratories. It also required dealing with the problems arising from the simultaneous running of several experiments. The ISR Committee had to cope with this kind of problem from the very beginning of its activity and recognized that careful consideration of questions concerning compatibility of groups of experiments was preliminary to definite conclusions about individual proposals.⁸² The Committee recommended that the experimental groups that had suggested similar arrangements of auxiliary equipment should agree on some form of common apparatus and it stressed that "experimental equipment [should] be designed for relatively easy removal in order that experiments can use the region in fairly rapid succession, or on an alternating basis."⁸³

As an example of this search for compatibility among different experiments, and also as an example of the decision-making process in this early phase, we can consider how the first experimental programme was arranged in two intersections, I-2 and I-6, the first devoted to the study of stable particle production, the second to proton-proton total cross section and proton-proton scattering.⁸⁴

The study of particle production in proton-proton collisions at ISR energies was independently suggested by several groups, following the call for proposals from the ISR Committee at the beginning of 1969. The most ambitious one, aimed at investigating the production spectra at low energy around 90°, was proposed by the so-called "Scandinavian Collaboration", a group of physicists from the universities of Bergen, Copenhagen, Lund, Stockholm, and Uppsala.⁸⁵ A significant aspect of the proposed experimental set-up was a large magnet providing a magnetic field of about 1 Tesla around the interaction region and

⁸² ISRC, 6th meeting (3-4/6/69), CERN/ISRC/69-40, 9/6/69.

⁸³ ISRC, 5th meeting (20-21/5/69), CERN/ISRC/69-35, 23/5/69, p. 3.

⁸⁴ The general layout of the planned ISR experiments just before its commissioning is presented in CERN/ISRC/71-4, 20/1/1971. A set of tables presenting the experiments at the ISR from 1971 to 1976, prepared by the ISR coordinators and coded CERN/ISR/EXP/1 to CERN/ISR/EXP/10, is in file EWDS 22324.

⁸⁵ The experiment proposal is presented in three documents: CERN/ISRC/69-2, 24/1/69; CERN/ISRC/69-16, 17/3/69; CERN/ISRC/69-17, 17/3/69. Also: Report ISRSc-ERL-69/13, 16/9/69 (CERN, K. Potter's files).

parallel to the colliding proton beams. This field did not affect the beams while allowing momentum analysis of the secondaries in a 2π solid angle with cylindrical symmetry around the beam direction. This magnet was considered with interest by the ISR Committee because of the possibility to use it "for further and more refined experiments."⁸⁶ Three other groups proposed experiments on particle production: a "British Collaboration", suggesting to search for intermediate bosons; a CERN Team, suggesting to measure multiparticle spectra; and a CERN/Holland-Lancaster/Manchester collaboration, which wanted to study particle production at large angles.

The Committee urged the four groups to discuss the possibility of a common apparatus and, following a meeting of their representatives, a report was presented to the Committee which acknowledged that "the British and Dutch proposals are not only compatible with each other but a combination of them at the same intersection would be desirable for both parties" and suggested intersection I-2 as suitable for the two combined experiments.⁸⁷ The Scandinavian experiment, on the other hand, could not be combined with them since it completely surrounded the interaction region. It was then suggested to arrange this experiment in intersection 1, provided that the experimental equipment was designed so as to be easily movable in order to share the available running time with another possible experiment. As to the CERN proposal, it was recognized that this experiment depended on the availability of a kind of magnet which was not expected to be available in the near future, so it was suggested that the CERN team should join the Scandinavian Collaboration.

It required more than two months and three ISR Committee meetings to decide to examine concretely all the proposals in the light of compatibility among groups of experiments which could be carried either simultaneously or alternately. At its 6th meeting, early in June 1969, the ISR Committee decided to reject the Scandinavian Collaboration's magnet and asked the Collaboration itself:

To examine the possibilities for use of this magnet in a wider scope than that of their original proposal, what features of the magnet would make it valuable as a general-purpose facility, and to compare it with

⁸⁶ ISRC, 2nd meeting (11-12/2/69), CERN/ISRC/69-10, 12/2/69, p. 1.

⁸⁷ CERN/ISRC/69-18, 17/3/69, p. 1.

other designs (for example, a central-field magnet) in providing complementary use with the split-field magnet.⁸⁸

The Committee then asked K. Winter to explore the possibility of arranging all experiments on particle production at intersection 2, including one more experiment proposed by a Collaboration from the Universities of Bologna and of Michigan.⁸⁹

Following a meeting of representatives of all interested parties it was finally agreed that different groups should be responsible for different angular regions: the CERN/Holland-Lancaster/Manchester Collaboration for the small angle region, up to 150 mrad; the Bologna/Michigan Collaboration for the medium angle region, starting at 100 mrad in order to reduce the overlap with the small angle spectrometer; the British Collaboration and a team of the Scandinavian group for large angles (from 300 mrad to $\pi/2$).⁹⁰ Opposite the large angle spectrometer, the British could install their muon detector to search for the intermediate boson. In fact, since the search for large-angle muons required a good knowledge of the spectrum of the pions, this experiment had to rely on the data collected by the other groups in the same region.

The arrangement, in fact, did not satisfy the Scandinavians who, while expressing their willingness to collaborate with other groups at intersection 2, insisted that their "main interest continues to be the study of particle correlations, which requires a detector of large solid angle." They also suggested a new experimental set-up of their original proposal and reiterated their request for intersection I-1.⁹¹ They did not succeed, however, as this intersection had already been committed with three other experiments, and the ISR Committee finally decided to recommend to the NPRC the arrangement suggested in Winter's report.⁹² The NPRC approved this arrangement and the four experiments, labelled R201 to R204, started at the very beginning of ISR operations.⁹³

⁸⁸ ISRC, 6th meeting (3-4/6/69), CERN/ISRC/69-40, 9/6/69, p. 5.

⁸⁹ CERN/ISRC/69-7, 17/2/69.

⁹⁰ CERN/ISRC/69-44, 20/6/69.

⁹¹ CERN/ISRC/69-48, 1/7/69.

⁹² ISRC, 7th meeting (3/7/69), CERN/ISRC/69-49, 3/7/69.

⁹³ Experiment R201 (particle production at small angles) was on the floor from August 1971 to March 1974; experiment R202 (particle production at medium angles) from May 1971 to

A somewhat similar pattern was followed for intersection 6. Here it was advised to set up the experiments on elastic scattering and total cross section, following the proposals of three groups, namely: a group from the University of Pisa (later in collaboration with a group from Stony Brook) who proposed to measure the total cross section; a CERN–Genova–Torino Collaboration (later with a group from Aachen) who proposed to measure the elastic scattering cross section; and a Rome (Istituto Superiore di Sanità)–CERN Collaboration who proposed to measure the elastic scattering cross section in the angular region of Coulomb scattering (i.e. at small angles).⁹⁴ A meeting between the representatives of the three groups was held, together with F. Bonaudi and G. Cocconi, and a possible scheme of operation was suggested according to which the Pisa experiment on total cross section alternated with a combined set-up of the two elastic scattering experiments running simultaneously and taking data in different angular regions, within and beyond the region of Coulomb scattering respectively.⁹⁵ From the practical point of view, the hodoscope of the Rome experiment could remain permanently installed while the apparatus of the other two experiments had to alternate over a period of a few months and a change-over time of 3–4 days. Further discussions among all future experimenters at the interaction region 6 helped to design a proper arrangement for the several instruments and to plan the experimental programme.⁹⁶

The scheme, however, proved unworkable: a few months before the start of operations the three groups became aware of the difficulties and conflicts involved in running their respective experiments in a single interaction region and therefore the ISR Committee suggested that a new intersection, I–8, should be opened to arrange the Pisa–Stony Brook experiment on total cross section.⁹⁷ The Committee

September 1971; experiment R203 (particle production at large angles) from July 1971 to December 1971; experiment R204 (search for the intermediate vector boson) from June 1971 to December 1973 (information from documents in files EWDS 22302 and EWDS 22324).

⁹⁴ ISRC, 6th meeting (3–4/6/69), CERN/ISRC/69–40, 9/6/69. These experiment proposals are, respectively, in CERN/ISRC/69–12, 14/3/69; CERN/ISRC/69–19, 16/3/69; CERN/ISRC/69–20, 24/3/69.

⁹⁵ CERN/ISRC/69–46, 30/6/69; ISRC, 7th meeting (3/7/69), CERN/ISRC/69–49, 3/7/69.

⁹⁶ CERN/ISRC/69–53, 12/9/69. The programme was eventually approved at the 8th meeting of the ISRC (23–24/9/69), CERN/ISRC/69–56, 26/9/69.

⁹⁷ CERN/ISRC/70–27, 16/11/70; ISRC, 17th meeting (17–18/2/71), CERN/ISRC/71–11, 4/3/71.

wanted to emphasize, however, that this was "an emergency measure [which] should not be interpreted as an opening up of this region for other experiments". This underlining appeared opportune as a previous request to open another interaction region for experiments had been turned down because of budgetary and other difficulties with respect to the overall CERN programme.⁹⁸ In the event, intersection 8 was definitely added to 1, 2, 4, and 6 as one of those exploited from the very beginning of ISR operations.⁹⁹

The Split-Field Magnet

It was early recognized that one of the interaction regions at the ISR had to be reserved for a large general purpose magnet system, capable of momentum analysing most of the secondary particles produced in proton-proton collisions. In order to avoid any perturbing effect on the beam orbits in the rings, a system of magnetic fields had to be designed which compensated each other in some way by suitable alternation of sign, so that the circulating protons, although deflected whilst passing through the system, reverted to their equilibrium orbit as they left the system. A few designs meeting this requirement were discussed in early 1968 at the open meetings of the Working Party on the experimental programme and a special *Study Group for large magnet detectors* was set up.¹⁰⁰

At the first Users' Meeting, in June 1968, several possible arrangements for general purpose magnetic systems were presented and extensively discussed. All of them considered vertical fields, so that deflections occurred in the horizontal plane, but could be distinguished in two classes: the first included a central analysing magnet, namely a magnetic field across the centre of the interaction region; the other had only downstream fields. In the words of the reviewer,

⁹⁸ ISRC, 12th (2-3/6/70) and 13th (13-14/10/70) meeting, CERN/ISRC/70-12, 5/6/70, and CERN/ISRC/70-23, 16/10/70. See also CERN/ISRC/70-17, 29/9/70.

⁹⁹ The Pisa-Stony Brook experiment became R801 and stayed on the floor from September 1971 to December 1974; the CERN-Rome experiment, code named R601, was on the floor from May 1971 to December 1972; the CERN-Aachen-Genova-Torino experiment (with the addition of groups from the University of California, Harvard, Munich, North Western, Riverside), was code named R602 and stayed on the floor in two phases from May 1971 to July 1974 (information from documents in files EWDS 22302 and EWDS 22324).

¹⁰⁰ Discussions on this subject were made at meetings No. 1, 5, 8, and 9. The conclusions of the Study Group were discussed at the 13th meeting.

It depends on the experimental programme which is preferable. Extrapolation from known interactions and perhaps speculation about unknown interactions should be decisive. Once the question about the central magnet is settled, it is believed that the sorting out of the remaining variants is readily obtained.¹⁰¹

In fact, while downstream magnets were necessary to analyse the many secondary particles emitted at small angles with respect to the direction of the colliding protons, a central field was useful if one wanted mainly to analyse particles produced at large angles. It depended on what one expected from proton-proton collisions in the ISR to make a choice between the two alternatives.

By the end of the year attention had concentrated on three systems, two of which were based on a central magnet with uniform field covering the interaction region while the third foresaw a large magnet providing fields of opposite polarity on either side of the interaction region and zero field at the crossing point itself (split-field magnet, hereafter SFM).¹⁰² In order to study these proposals in detail and to make a choice, a special working party was set up by the Director General of CERN, which eventually submitted a report.¹⁰³ Behind the technical comparison between the three designs, the real issue was the choice between two radically different experimental interests. On the one hand, the main proponent of the split-field magnet system, CERN's physicist and Nobel Prize winner J. Steinberger, could claim that all experimental evidence so far confirmed that hadronic collisions produce secondary particles (pions and other hadrons) largely concentrated at small angles and therefore that was the region to be privileged in investigations at higher energies.¹⁰⁴ On the other hand, the main supporter of central field systems, the American physicist G. O'Neill (who was also one of the fathers of the storage rings idea), stressed the importance of covering as much as possible of the solid angle around the intersection region as well as the necessity

¹⁰¹ F. Krienen, "Review of proposed magnetic analysis systems for ISR reactions", report presented at the first ISR Users' Meeting (10–11 June 1968), p. 10, NP 22898.

¹⁰² French et al. (1968); Hyams & O'Neil (1968); Steinberger (1968). See also Resegotti (1969).

¹⁰³ Winter (1969).

¹⁰⁴ According to L. Di Lella's recollections, G. Cocconi used to say: "Let's forget 90°. Nothing happens at 90°"; interview with A. Russo and J. Krige, 29/8/90.

of making good momentum measurements both on charged hadrons and on electrons and muons.¹⁰⁵

O'Neill's suggestion was to prove more far-sighted, as we shall see, but it did not succeed. At the 3rd meeting of the ISR Committee, in fact, Director General B. Gregory reported that it had been decided to build "a simplified version of the so-called split-field magnet."¹⁰⁶ No explicit reason for this choice could be found in the files, but one may venture to suggest that the prestige and influence of Steinberger, on the one hand, and a kind of sound conservatism which led to look at the ISR in terms of extrapolation from known results, on the other, determined the decision of CERN's directorate. This decision did not please O'Neill, however, and, as his following proposal for an experiment based again on a special magnet was also rejected by the ISR Committee, he decided to drop any collaboration with CERN.¹⁰⁷

The Magnet Group of the ISR Department was charged to build the magnet proposed by Steinberger while G. Charpak and A. Minten were to coordinate a working group on the detection apparatus and other equipment to be associated with the magnet, "both in the light of the proposed experiments that may use this magnet and in the light of what may be needed for the entire system to be used as a general facility."¹⁰⁸ A set of large multi-wire proportional chambers developed

¹⁰⁵ G. O'Neil, *A detector with large solid angle*, paper presented at the second ISR Users' Meeting (2-3/12/68), CERN/68 ISRU/119. The interest in looking for electrons and muons at large angles derived from the fact that they were expected to be decay products of intermediate vector bosons (IVBs).

¹⁰⁶ ISRC, 3rd meeting (18-19/3/69), CERN/ISRC/69-21, 25/3/69, p. 2.

¹⁰⁷ O'Neill's proposal is in CERN/ISRC/69-23, 31/3/69, and CERN/ISRC/69-30, *date*. It was discarded at the 6th meeting of the ISRC (3-4/6/69), CERN/ISRC/69-40, 9/6/69. See also Gregory's letter to O'Neill, 6/6/69, in CERN Archive, K. Potter's files. Negotiations about eventual involvement of O'Neill in the ISR experimental programme had been discussed since the end of 1965 (the relevant correspondence can be found in file MGNH 22007). After the choice of the split-field magnet and the dropping of his experiment proposal, O'Neill had been invited to join the group which was building the detectors for the SFM to perform a survey programme of test experiments before the installation of the magnet: CERN/ISRC/69-54, 15/9/69; CERN/ISRC/70-05, 17/4/70; ISRC, 7th meeting (3/7/69), CERN/ISRC/69-49, 3/7/69; ISRC, 8th meeting (23-24/9/69), CERN/ISRC/69-56, 26/9/69; ISRC, 12th meeting (2-3/6/70), CERN/ISRC/70-12, 5/6/70.

¹⁰⁸ ISRC, 4th meeting (22-23/4/69), CERN/ISRC/69-33, 23/4/69, p. 3.

by Charpak was eventually chosen as the basis for the experimental apparatus at the SFM.¹⁰⁹

In the event, the ISR Committee felt it should not commit itself too much with CERN's physicists in the future exploitation of the SFM facility and asked Charpak and Minten's group to request wider collaboration outside CERN.¹¹⁰ Two groups, in particular, had expressed interest in participating in the building and testing of SFM detectors and they then joined the CERN group in a test and survey programme which was approved by the ISR Committee.¹¹¹

In spring 1971, just after the commissioning of the ISR, the ISR Committee held an open session to review the progress work on the SFM facility and urged experiment proposals for using it.¹¹² In October several proposals were on the table and, after discussion at an open meeting, the ISR Committee approved a number of experiments to be run in the first phase of SFM operation.¹¹³ At the same time, the Committee suggested that CERN appointed an SFM co-ordinator for planning and managing the experimental programme at this facility, taking as a model the co-ordination of experiments for the Omega Spectrometer. In the event, K. Tittel was appointed as the first SFM co-ordinator.

In May 1973, the 1000 tons complete magnet was carried from the assembly hall to intersection I-4 and accurately positioned. The first physics run of the SFM facility was then successfully performed at the end of August and the first experiments started taking data. By the end of the year, the SFM facility had been

¹⁰⁹ Charpak et al. (1968). See also Gambaro (this volume).

¹¹⁰ ISRC, 5th meeting (20-21/5/69), CERN/ISRC/69-35, 23/5/69.

¹¹¹ ISRC, 12th meeting (2-3/6/70), CERN/ISRC/70-12, 5/6/70, p. 4. See also CERN/ISRC/69-45, 2/7/69. The groups involved were a CERN-Münich-Princeton Collaboration and a CERN-Hamburg-Orsay-Vienna (CHOV) Collaboration. Their original proposals are CERN/ISRC/69-8, *date* and CERN/ISRC/69-14, 14/3/69, respectively. Princeton's contribution in the first collaboration was that of O'Neill who eventually disappeared. The test and survey programme is described in CERN/ISRC/69-54, 15/9/69, and CERN/ISRC/70-5, 17/4/70.

¹¹² ISRC, 19th meeting (28/4/71), CERN/ISRC/71-20, 5/5/71. The report on the situation of the SFM is CERN/ISRC/71-19, *date*. By that time, only one proposal had been accepted, namely that presented in 1969 by the CHOV collaboration (CERN/ISRC/69-14, 14/3/69). Another proposal, presented by a group led by A. Zichichi and aimed at quark searching, had been rejected (CERN/ISRC/70-31, 8/12/70, and Add. 1, 14/5/71).

¹¹³ ISRC, 23rd meeting (19-20/10/71), CERN/ISRC/71-44, 21/10/71. See also CERN/ISRC/72-21, 13/7/72.

in operation for about 300 hours for physics, with beams at all standard energies and beam currents from 3 to 7.5 A.¹¹⁴

Keyhole physics

The experimental programme set up for the first phase of operation of the ISR clearly reflected a policy aimed at offering as many experimental groups as possible the opportunity to work with CERN's new accelerator. The ISR Committee and the CERN establishment did not want to give one group the monopoly of experimentation at one of the intersections or the exclusive right of pursuing a specific scientific objective. This policy was in the tradition of CERN and derived from the laboratory's multinational personality.

At the same time, the experimental programme at the ISR also reflected the lack of experience with collider physics. Physicists both within and without the ISR Committee designed ISR experiments with the same approach used with fixed target accelerators where, due to the kinematics of the collisions, one has the compression of most of the solid angle in the centre-of-mass into small laboratory angles with respect to the beam. The particles emitted at large angles are mainly fragments of the target hadrons while most secondary particles are produced in the forward direction. Therefore it appeared reasonable to allot each experiment one small wedge in the imaginary sphere surrounding the collision point with a strong bias towards small angles. This is what was eventually called "keyhole physics".¹¹⁵

It was realized too late that, due to the kinematics of head-on collisions and to the newly discovered phenomena, the whole laboratory solid angle was important and a completely different approach was required; experiments had to be based on detectors covering as much as possible the region around the collision point in order to investigate events occurring at large angles that are usually mixed up with those at small angles in fixed target collisions and to study correlations among secondary particles.

¹¹⁴ CERN, *Annual Report*, 1973, p. 119.

¹¹⁵ Jacob (1984), p. 35. C. Rubbia's harsh criticism against keyhole physics is reported by Taubes (1989), p. 45–46.

Among the very first experiments proposed at the ISR, that of the Scandinavian Collaboration provided an example of what would have been a more suitable approach to ISR physics. As a matter of fact, the axial field magnet proposed by the Scandinavians represented a completely different experimental philosophy with respect to the vertical-field magnet systems under discussion at that time for intersection I-4. The ISR Committee could not accept it as a specific experiment for it would have monopolized a whole intersection; on the other hand, it did not feel up to accepting it as a general facility in competition with the SFM. The decision not to accept the magnet proposed by the Scandinavians, a political as well as a scientific decision in the light of the above considerations, appears *a posteriori* a missed opportunity to have such a kind of magnet spectrometer available at the very beginning of ISR operations.

One would be tempted to ascribe the timidity and delays in equipping the ISR with big detectors to some "strong element of conservatism in the early experiments and in the experimental selection procedures."¹¹⁶ As a matter of fact, some cultural inertia and conservatism is always present in big science and it is hard to expect the management of a large international laboratory to undertake revolutionary steps. The whole of project proposals with a quite new experimental field is always richer and riskier than the set of approved projects and extrapolation usually prevails over speculation. In the case of CERN, there was the established tradition to give many experimental groups a chance to work at the Laboratory's accelerators and any big equipment was intended as a facility open to interested users.

But it is not only a matter of policy and management. Running the ISR was a scientific novelty and a technical challenge from the experimental point of view. Most physicists with an experience in the study of hadronic interactions at fixed target accelerators approached the new machine with their cultural biases and designed their experiments according to their standard practice. By the end of the 1960s, when the first experimental programme at the ISR was defined, there was no adequate theory of strong interactions and the new machine had been built without any specific scientific goal other than to probe much higher energies where some kind of asymptotic behaviour was expected. Most physicists

¹¹⁶ Albrow (1983), p. 745. Albrow's opinion has been questioned by Di Lella (1984).

interested in strong interactions looked at p-p collisions at the ISR as they used to do at the PS: study of particle production at small angles and measurement of cross sections. The people who were interested in large angle were those who searched for rare events like the production of electrons or muons from the decay of intermediate vector bosons $W^\pm$ and Z^0 .¹¹⁷

Another factor that probably affected negatively the timely development and implementation of large detectors for the ISR was the rather lukewarm interest of many physics leaders towards this accelerator. This machine had been strongly advocated by accelerator physicists and engineers but particle physicists had tolerated it only as an unfortunate step towards their favourite project for a 300 GeV accelerator.¹¹⁸ We may remember, for example, the strong opposition of L. Van Hove to the ISR and we can guess that when he became CERN's Director General for Research, in 1976, this attitude had something to do with the decision of the Research Board, in November that year, not to follow the recommendation of the ISR Committee to build a big solenoid as a new magnetic facility.¹¹⁹

The case of this solenoid is interesting. By May 1975 an ambitious proposal to build a large axial field spectrometer, based on a superconducting solenoid, was presented by a collaboration of seven scientific institutions. The aim was to investigate the production of hadrons with high transverse momentum, the most important phenomenon discovered at the ISR.¹²⁰ After considerable discussion, extending over three meetings, the ISR Committee decided not to recommend this proposal.¹²¹ The issue of a new magnetic facility for the ISR remained, however, and a special Working Party was formed to study possible designs. Two

¹¹⁷ We shall deal with these ISR experiments later. The intermediate vector bosons required a much higher energy than at the ISR to be produced and were eventually discovered at the SPS pp-collider.

¹¹⁸ Pestre (1990 b).

¹¹⁹ ISRC, 69th meeting (10/11/76), CERN/ISRC/76-33, 16/11/76. Research Board, 11th meeting (25/11/76), CERN/RB/11.

¹²⁰ The proposal is described in CERN/ISRC/75-18, 12/5/75; CERN/ISRC/75-21, 25/6/75; CERN/ISRC/75-37, 30/9/75. The collaboration included three Scandinavian Institutions (the Universities of Bergen and Lund and the Niels Bohr Institute in Copenhagen), three American institutions (the Universities of Harvard and Illinois and the Lawrence Berkeley Laboratory) and the Rutherford Laboratory (U.K.).

¹²¹ ISRC, 58th meeting (11/7/75), CERN/ISRC/75-23, 14/7/75; 59th meeting (10/11/75), CERN/ISRC/75-35, 11/9/75; 60th meeting (15/10/75), CERN/ISRC/75-40, 16/10/75. In the minutes of these meetings no reason for this rejection is explicitly given.

alternative devices were discussed in detail, a solenoid magnet and a toroidal magnetic field, and the ISR Committee recommended the solenoid. As we have anticipated, the CERN Research Board decided, however, not to follow this recommendation and dropped the project.¹²² Eventually, a less ambitious project was approved, based again on an axial field magnet associated with a drift chamber detector and a uranium calorimeter. This facility was built at intersection I-8 (experiment R807) but it started to operate only in 1980, when the 300 GeV was already providing spectacular results and the future of the ISR was definitely endangered.¹²³

A second case which evidences the unwillingness of the ISR management to undertake the construction of big detectors is the story of the large calorimeter proposed by C. Rubbia in 1972. Rubbia was certainly among those who understood from the beginning the novelty of collider physics and, in particular, the need for large detectors surrounding the intersection. In November 1972 he and his collaborators presented a proposal for "a large 4π detector to investigate multibody events at the ISR."¹²⁴ The physics motivation and the experimental philosophy of the proposed experiment expressed a radical departure from established practice:

One of the most striking features of the ISR energy range is the spectacular complexity of the events. [...] How can we visualize the physics contained, for instance, in a fifty or more prong event ? Single particle spectra, two or more particle correlations of course are very likely averaging over a greater fraction of the information. Evidently the single particle behaviour is probably irrelevant and one must concentrate on more global properties of each event. [...] A main experimental problem is the one of selecting with good efficiency the

¹²² *Report of the ISR Working Party*, January–August 1976, in file DGE 21561. ISRC, 69th meeting (10/11/76), CERN/ISRC/76–33, 16/11/76. Research Board, 11th meeting (25/11/76), CERN/RB/11.

¹²³ The proposal was presented by a CERN–Lund–Copenhagen–Rutherford Collaboration: CERN/ISRC/76–36 (P 95), **date**; CERN/ISRC/77–7, **date**; CERN/ISRC/77–11, **date**. ISRC, 70th meeting (12/1/77), CERN/ISRC/77–3, 13/1/77; 71st meeting (16/2/77), CERN/ISRC/77–5, 17/2/77. The detector is described in Fabjan *et al.* (1978).

¹²⁴ The proposal was worked out by a Aachen–CERN–Harvard–Genova Collaboration and was described, with successive modifications, in CERN/ISR/72–32, 9/11/72, and add. 1–5, 16/2/73 to 14/10/73.

relevant type of events out of the fantastically large number of p-p interactions. This is possible only provided several physical quantities like transverse momenta, multiplicity etc. are directly accessible to very fast decision-making electronics.¹²⁵

The apparatus was based on a 4π total absorption calorimeter consisting of a large segmented sphere, filled with liquid scintillator, completely surrounding the intersection. This was an instrument of which the "unconventional nature" and "unusual size" was explicitly acknowledged and that was presented as "completely complementary" to the Split-Field Magnet.¹²⁶

The proposal was discussed at the ISR Committee at the beginning of 1973, together with two others also suggesting total absorption detectors, but all were rejected.¹²⁷ A new design was then worked out by Rubbia's group, based on a hybrid device in which two small calorimeters were used to study the forward jets and the large angles were covered by the magnetic spectrometer installed at intersection I-6 for experiments R602 and R603. Compared with the original proposal, the new detector was much smaller and lighter and considerably less expensive. The ISR Committee discussed the new project in August 1973 and encouraged the group to continue studies for this experiment; almost one year later, however, the proposal was definitely rejected.¹²⁸

Keyhole physics at the ISR was to predominate until 1977-1978, when new wide-angle magnetic spectrometers started operation. In particular: the superconducting solenoid detector at I-1 and the magnetic toroid spectrometer at I-2 for lepton-pair studies; the Axial Field Spectrometer and argon calorimeter at I-8 for large transverse momentum phenomena; the upgraded Split-Field Magnet. After the important results of the first period of operation (1971-1974) and the difficult period when the ambitious detectors which were needed were not yet

¹²⁵ CERN/ISRC/72-32, 9/11/72, p. 1, 3.

¹²⁶ CERN/ISRC/72-32, 9/11/72, p. 10, 16.

¹²⁷ ISRC, 34th meeting (24/1/73), 25/1/73, and 35th meeting (21/2/73), 23/2/73. The two other proposals were presented by P. Darriulat, on behalf of the Aachen-CERN-München Collaboration already involved in experiment R701, and by the American W.J. Willis, of Yale University and Brookhaven National Laboratory: CERN/ISRC/72-30, 10/11/72 (with add. 1 and 2, 10/1/73); CERN/ISRC/73-1, undated.

¹²⁸ ISRC, 40th meeting (7/8/73), CERN/ISRC/73-25, 9/8/73; 41th meeting (16/10/73), CERN/ISRC/73-31, 18/10/73; 49th meeting (28/6/74), CERN/ISRC/74-32, 2/7/74.

available (1974–1978), ISR physics could again find a respectable place in the highly competitive terrain of particle physics.¹²⁹

Particle physics in the 1970s

The period of operation of the ISR coincided with a dramatic change in high energy particle physics and, in order to better understand the merits and limits of the physics made at the Rings, a short review of this research field in the 1970s is useful.¹³⁰ By the late 1960s particle physics was dominated by the study of strong interactions, with its multitude of data on cross-sections and resonances. Protons were regarded as extended objects and their collisions were essentially soft, producing secondaries mostly concentrated in a very limited solid angle along the direction of motion of the colliding particle. The quark model had been suggested to explain the resonance population while the Regge-pole theory provided a general framework for hadronic phenomena. Going to higher and higher energy in hadron physics looked the most promising path to simplicity.¹³¹

Ten years later, after electron and neutrino deep scattering experiments, the discovery of charmed particles and the merging of the concept of quarks and the concept of partons, a new tradition had been firmly established, based on the Standard Model of quantum chromodynamics and unified electroweak interactions.¹³² In the new framework, protons, while still extended and complicated objects, were made of point-like constituents and the most interesting phenomena could be observed at wide angle by detecting leptons, photons and hadrons, isolated or correlated in jets, which are produced by the interactions of these constituents. Hard scattering experiments involving leptons and partons seemed the new Promised Land of experimental particle physics.

This almost about-turn in our approach towards hadron physics [...] took place as research at the ISR was already well under way and, to

¹²⁹ For this periodization see Jacob (1984).

¹³⁰ Useful historical reviews are Pickering (1984), Crozon (1987), Cahn & Goldhaber (1989). See also Watkins (1986).

¹³¹ For a review of Regge theory, as it was applied to hadronic processes by early 1970s, see Collins (1971) and Horn (1972).

some extent, benefiting from it with the discovery of an anomalous high production of hadrons at large transverse momentum, in 1972. The history of physics at the ISR, as one is now able to contemplate with some hindsight, indeed appears to be characterized by this mutation of what is more fundamental in hadronic interactions.¹³³

Hard scattering, partons and quarks

At the beginning of the transition between particle physics in the 1960s and the "new physics" of the 1970s there was an important result obtained at the Stanford Linear Accelerator Center (SLAC) in 1969. Experiments performed at the new 22 GeV, two-mile long, linear electron accelerator showed that energetic electrons were inelastically scattered from protons at large angles with a probability much larger than one would expect if the charge of the proton were smoothly distributed over its volume. These data were interpreted by J.D. Bjorken as a manifestation of the *scaling* phenomenon and, after a suggestion by R. Feynman, this phenomenon was explained in terms of a structure of point-like constituents of the proton called *partons*. In the parton-model explanation of *scaling*, the deep inelastic electron-proton scattering was visualised as a process wherein the incoming electron interacts with a single free parton in the proton by the exchange of a photon (fig. 8).¹³⁴

The discovery of point-like structures inside the proton was soon connected with the quark hypothesis. The latter, however, was a highly abstract theoretical model which had been introduced in the old physics of resonance phenomena as a possible classification scheme of hadrons. It required a good deal of theoretical effort to put quarks and partons in a coherent framework which included *gluons* and a quark-antiquark "sea" as components of the hadrons.¹³⁵

¹³² Marciano & Pagels (1978), Harari (1978), Altarelli (1981), Wilczek (1982).

¹³³ Jacob (1984), p. 26.

¹³⁴ Bloom *et al.* (1969); Breidenbach *et al.* (1969); Bjorken (1969); Bjorken & Paschos (1969); Feynman (1972). See also Kogut & Susskind (1973) and Yan (1976).

¹³⁵ Kuti & Weisskopf (1971); Drell & Yan (1971); Friedman & Kendall (1972); Kogut & Susskind (1973); Feynman (1974).

The quark-parton model drew its early empirical support from electron-scattering experiments; other processes on which experimental information became available in the late 1960s and early 1970s were conceptualised in terms of the quark-parton model and came to constitute important strands of particle physics in the 1970s. In particular, the neutrino scattering experiments with CERN's new large bubble chamber *Gargamelle*, which led to the discovery of neutral currents, confirmed the validity of the model also in the domain of weak interactions and stimulated the rapid growth of neutrino physics (fig. 9).¹³⁶

Other processes involved the production of lepton pairs (e^+e^- or $\mu^+\mu^-$) in proton-proton collisions. The first important experiment in this field was made in 1968–69 at the Brookhaven AGS by a Columbia University group led by L. Lederman.¹³⁷ The primary aim of Lederman's experiment was the search for intermediate vector bosons (IVB) by detecting the $\mu^+\mu^-$ pairs expected to be their decay products. They failed, of course, to find any IVBs (the energy was far too low) but, as Lederman recalled later, their results "stimulated a flood of theoretical attempts to account for one feature of the data – a continuum distribution of dimuon masses [...]. When the dust had settled, the most often quoted and used model was that of Drell–Yan".¹³⁸ According to this model, a lepton pair (electrons or muons) emerged from a virtual photon created by the annihilation of a quark from one of the protons with an anti-quark from the other (fig. 10).

Lederman's results, interpreted in terms of the Drell–Yan model, placed experiments on inclusive lepton-pair production in the stream of the new ideas and perspectives opened by the deep-inelastic electron scattering experiments.¹³⁹ This kind of experiment, however, was very hard to perform because the few

¹³⁶ Eichten *et al.* (1973); Deden *et al.* (1975); Musset & Vialle (1978). Excellent historical analyses of the discovery of neutral currents are Galison (1983) and Galison (1987), 135–241.

¹³⁷ Christenson *et al.* (1970); Christenson *et al.* (1973); Lederman (1976).

¹³⁸ Lederman (1976), p. 153. Drell & Yan (1970) and (1971). It must be noted that a "curious protuberance between 3 and 4 GeV" had been observed in the smooth curve found by Lederman, which was the first signal of the J/ψ particle, not recognized at that time and then discovered in 1974, as we shall see.

¹³⁹ Lederman (1976), Craigie (1978), Stroynowski (1981). An *inclusive* experiment is when one is interested in detecting one particular product of the reaction regardless of others. An *exclusive* experiment is when one wants to study all events produced in a particular reaction. This distinction was introduced by Feynman (1969). Inclusive experiments based on the use of electronic detectors became more and more characteristic of the new particle physics in the 1970s.

lepton pairs expected had to be detected in the high background of hadrons produced in proton-proton collisions. The same phenomenon could be studied in a much cleaner way in electron-positron collisions (the inverse process, fig. 11) and, in fact, e^+e^- colliders became the topical machine for this kind of investigation in the 1970s.¹⁴⁰

The "November revolution"

By the end of 1974, the new experimental traditions on hard scattering processes were still a minority compared with the dominant soft-scattering traditions.¹⁴¹ From the theoretical point of view, the discovery of neutral currents in 1972-73 had confirmed the validity of unified gauge-theory models of electroweak interactions but, on the other hand, the gauge theory of coloured quark and gluons named quantum chromodynamics (QCD) received relatively little attention from the point of view of phenomenological applications because of its weakness in explaining the strict confinement of quarks and gluons inside the proton.

In November 1974 the discovery was announced of a new, very massive (3.1 GeV) particle which, due to its simultaneous revelation in two different laboratories, received and kept a double name: J/ψ . It was discovered at the Stanford electron-positron collider SPEAR by a SLAC-LBL collaboration led by B. Richter and G. Goldhaber (ψ) and at the Brookhaven AGS by an MIT group led by S. Ting (J). The former were investigating e^+e^- annihilation to hadrons; the latter were investigating e^+e^- pair production by hadrons.¹⁴² In the following months, evidence for the existence of further particles belonging to the same family came from electron-positron machines and, by mid-1976, it was generally

¹⁴⁰ Early experimental information on electron-positron annihilation with regard to the quark-parton model came from the e^+e^- collider ADONE which began operation at Frascati, Italy, in 1967. Between 1972 and 1980 seven e^+e^- colliders started to operate: SPEAR at SLAC (1972), DORIS at DESY (1974), DCI at Orsay (1976), PETRA at DESY (1978), CESR at Cornell (1979), PEP at SLAC (1980), VEPP-4 at Novosibirsk (1980).

¹⁴¹ Pickering (1984), p. 235-238, reviews the situation in the light of the proceedings of the 17th International Conference on High Energy Physics, held in London in July 1974.

¹⁴² Augustin *et al.* (1974); Aubert *et al.* (1974). Personal recollections of this discovery are Ting (1977) and Richter (1977). Two weeks later, the SPEAR experimenters found a second member of this family, at 3.7 GeV, which was called ψ' : Abrams *et al.* (1974).

accepted that the new particles were manifestations of a new quark, carrying the charm quantum number which had been postulated in the framework of the unified electroweak gauge theory.¹⁴³ This theory thus became the standard model upon which all subsequent experimental programmes on weak interactions were organized: the rise to prominence of electron–positron annihilation physics and of neutrino physics was amongst the most important effects which sprang out from the "November revolution".

The charm explanation of the new particles also represented a successful application of quantum chromodynamics and encouraged further theoretical elaboration: as a consequence, the existence of quarks as components of hadrons was put beyond dispute and QCD became the basis of a new hadron spectroscopy. Again, this caused a significant shift in experimental practice at proton synchrotrons: existing experimental programmes on hard-scattering were reinforced and new programmes were designed to investigate the production and properties of charmed particles using photon, neutrino and hadron beams.

A brief analysis of the experimental apparatuses used in 1974 at Brookhaven and Stanford to detect the J/ψ particle can give an idea of the new paths of experimental particle physics which the ISR scientific management were called to develop. At the Brookhaven 33 GeV proton synchrotron, Ting and his collaborators were aiming at the same objective as Lederman's, namely to search for massive particles which decay into lepton pairs, in this case electron–positron pairs. The problem was to detect these rare e^+e^- pairs and to measure their physical parameters in the large hadronic background. The apparatus built by the MIT group, which drew from Ting's early experience at DESY, consisted in a very sophisticated double-arm spectrometer, each arm including three magnets, 8000-wire proportional chambers, Cherenkov counters and lead-glass calorimeters (fig. 12). A pure electron beam for calibration and a shielding consisting of 10,000 tons of concrete, 100 tons of lead, 5 tons of uranium and 5 tons of soap completed the experimental setup. Owing to its complexity, the detector required six physicists to operate it and, before each data-taking run, about 100 hours were spent ensuring that all the detectors worked with 100 % efficiency. According to Ting,

¹⁴³ Glashow, Iliopoulos & Maiani (1970).

During the construction of our spectrometer, and indeed during the entire experiment, I encountered much criticism. The problem was that in order to gain a good mass resolution it was necessary to build a spectrometer that was very expensive. One eminent physicist made the remark that this type of spectrometer is only good for looking for narrow resonances – and there are no narrow resonances. Nevertheless, since I usually do not have much confidence in theoretical arguments, we decided to proceed with our original design.¹⁴⁴

It is interesting to remark that Ting's ambitious programme included the installation of three experimental apparatuses: one at the electron synchrotron DESY at Hamburg for small mass values (0.5 to 2 GeV), that at the Brookhaven AGS for intermediate mass values (1.5 to 5 GeV) and a third at the ISR for high mass values (5 to 50 GeV). After discussing Ting's proposal, the ISR Committee "expressed its interest in the physics of this experiment" but eventually rejected it, a decision "motivated in part by the heavily loaded program for the SFM facility."¹⁴⁵

At Stanford, the SLAC group led by Richter and the Lawrence Berkeley Laboratory group led by Goldhaber built a huge magnetic detector, called Mark I, which completely surrounded the point where the electron and positron beams of the SPEAR storage ring came into collision (fig. 13).¹⁴⁶ The Mark I magnet produced a solenoidal field, coaxial with the beams, of about 4 kG throughout a volume of 20 m³. Particles moving radially outward from the beam–interaction point passed successively through a trigger counter, 16 concentric cylindrical wire chambers, a cylindrical array of 48 scintillators, a cylindrical array of 24 lead–

¹⁴⁴ Ting (1977), p. 241. Indeed, the J/ψ resonance proved to be very narrow.

¹⁴⁵ Ting's ISR proposal is in CERN/ISRC/73–9, **date**, with add. 1, 2, 3. The proposal was discussed by the ISR Committee at its 39th meeting (10/7/73) and rejected at its 40th meeting (7/8/73): CERN/ISRC/73–22, 11/7/73, p. 3; CERN/ISRC/73–25, 9/8/73, p. 4. See also Crozon (1987), p. 234–235.

¹⁴⁶ Richter had been the moving force behind the construction of the SPEAR electron–positron storage ring at SLAC. This facility started operation in 1972. After the small e^+e^- facilities in Frascati (ADONE) and in Cambridge, SPEAR marked the real arrival of e^+e^- physics.

scintillator shower counters and an additional array of spark chambers to separate muons from hadrons.¹⁴⁷

From this description of the apparatuses which were responsible for the most important and dramatic discovery in particle physics in the 1970s, one can easily understand how major future experiments in this research field would be characterized by highly sophisticated electronic triggers and 4π detectors. The following quotation from a well documented historical account of particle physics gives an idea of the implications of the "November revolution" from the experimental point:

Whilst e^+e^- machines had the advantage in producing a very clear signal of the existence of massive long-lived particles, other machines had the advantage in energy, intensity, and variety of quantum numbers which could be produced. [...] Thus three general categories of experiment moved to the centre of attention during the period from 1974 to 1976: e^+e^- annihilation; neutrino scattering; and general investigations of heavy particle production using lepton or hadron beams. The experimental tradition which was least affected by this transformation was that which was most productive: high energy hadron scattering at proton synchrotrons. Certainly charm searches did get under way at these laboratories, but these in no sense provided for full utilisation of the available facilities. In hadronic scattering the old-physics traditions of experiment persisted, so too did the old theoretical traditions which fed upon them. In the event, though, the old-physics traditions of experiment soon went into decline.¹⁴⁸

From 1976 onwards, in spite of persisting difficulties, the new physics was established: "Experimenters sought to isolate and explore the rare, small cross-section processes of particular significance in the gauge-theory world-view [and] the properties of the new particles were held to demonstrate the reality of

¹⁴⁷ Richter (1977), p. 253.

¹⁴⁸ Pickering (1984), p. 271–272. An important aspect discussed by Pickering is that the "November revolution" actually reconciled experimental particle physics with the theoretical work of field theorists involved in the construction of gauge theories of weak and strong interactions. See also Crozon (1987), p. 265–285

quarks."¹⁴⁹ The Weinberg–Salam electroweak model and hadron spectroscopy based on quantum chromodynamics were establishing themselves as the new paradigm in particle physics.¹⁵⁰ And in 1977 a second important discovery was made which confirmed the validity of the paradigm: the discovery of the Y particle by L. Lederman and his collaborators at Fermilab.¹⁵¹ Lederman, who had missed the discovery of the J/ψ , had installed an experiment similar to Ting's but they searched again for $\mu^+\mu^-$ pairs instead of e^+e^- pairs. The new particle revealed the existence of a fifth quark, the b -quark, that was a member of a doublet whose existence was required by theoretical considerations.

By the late 1970s, experimental activity in high energy particle physics was essentially planned within the framework of the new physics and could avail itself of a new generation of sophisticated electronic detectors and of the new set of e^+e^- colliders especially designed for it: PETRA at DESY (1978), CESR at Cornell (1979), VEPP-4 at Novosibirsk (1980) and PEP at SLAC (1980). At Fermilab, plans were started to install superconducting magnets in order to reach 1 TeV energy (the Tevatron, inaugurated in 1984). At CERN, Rubbia's project to transform the SPS into a pp^- collider was approved and the new facility started operations in 1981. In that same year, the project for LEP entered the development phase.

To the process which caused a mutation of particle physics in the course of the 1970s, the ISR contributed one important discovery and a set of significant results but it could not be a main protagonist of the change: "As a purely hadronic machine, the ISR was the hardest of hard cases for the new physics."¹⁵² It produced proton–proton collisions when the best machines for the new physics were electron colliders; it allowed higher centre of mass energies but its lower luminosity prevented the analysis of the most interesting rarer events of the new physics. It required highly sophisticated detectors to investigate the new phenomena but when they became fully operative at the rings the forthcoming opening of the new SPS pp^- Collider promised (and started to give) more

¹⁴⁹ Pickering (1984), p. 353 and 254.

¹⁵⁰ I use this concept in the sense of Kuhn (1970). In 1979 S. Weinberg, A. Salam and S.L. Glashow shared the Nobel Prize for their seminal theoretical work on electroweak unification.

¹⁵¹ Herb *et al.* (1977). See also Lederman (1978).

¹⁵² Pickering (1984), p. 352.

spectacular results. The ISR could only follow in the wake of the main scientific events of the transition process rather than create them. Its importance was not so much in the results it obtained as in the invaluable experience it gave for the next generation of CERN colliders, the SPS pp- collider and the LEP.

ISR physics

The period of operation of the ISR covered about 13 years, from March 1971 to December 1983. The experimental programme which developed at the Rings included 63 experiments, many of them corresponding to a research programme extending over several years and covering several topics. The number of groups involved in ISR experiments was well over 200, of which there were 44 from CERN, 119 from Member State institutions and 58 from institutions in the rest of the world (45 in the United States).¹⁵³ It is not possible to cover here the whole of this programme. Extensive reviews have been published and some of the most significant results will be dealt with in the chapters devoted to the development of physics at CERN in this period.¹⁵⁴ I will limit myself to discuss a few aspects which I consider more significant and to make reference to those experiments which help to place ISR physics in its proper historical context.

A "brilliant start" ¹⁵⁵

The early ISR experimental programme was essentially a beam survey programme based on the traditional "old physics" approach to the study of pp collisions. Three experiments (R601, R602, R801) were devoted to measurements of the total cross-section and to investigating elastic scattering, with the aim of studying the high-energy asymptotic region expected in the framework of the Regge theory. At intersection 2, three experiments (R201, R202, R203) shared the experimental hall to study particle production at small, medium and large angles respectively. One experiment (R103) can be considered as definitely belonging to

¹⁵³ Jacob (1984), p. 74.

¹⁵⁴ Reviews on ISR physics are Giacomelli & Jacob (1979), Jacob (1984).

¹⁵⁵ Jacob (1984), p. 33.

the territory of the "new physics".¹⁵⁶ The aim of the experiment, designed by a CERN–Columbia–Rockefeller Collaboration, was to study the production of electron pairs (e^+e^-) at large angles and it was, in fact, the follow-up of Lederman's Brookhaven experiment. The idea to repeat this experiment at the ISR had been suggested by CERN's physicist L. Di Lella after a period of stay at Lederman's laboratory at the Columbia University.¹⁵⁷ The ISR experiment differed from that at Brookhaven in that it looked for electron pairs instead of muon pairs and allowed a better mass resolution. It differed from other ISR experiments on particle production in that its detectors covered a large fraction of the solid angle around the intersection: they consisted of two symmetric arrays of wire spark chambers, plastic scintillators and lead–glass counters at 90° with respect to the beams' direction.

The ISR's beginning was "a brilliant start". In spite of its highly sophisticated technology the machine worked outstandingly in all components; the luminosity rose rapidly by two orders of magnitude, reaching the design value of $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ in about two years; the particular organization required for experimental work around the rings worked smoothly and important results were obtained which brought to light unexpected features in proton–proton interactions at very high energy. Two of them have deserved a place in textbooks on particle physics.

The first derived from the experiments on total cross-section and elastic scattering.¹⁵⁸ Two groups, as we have seen, had set up experiments on this topic at intersection 6 and one at intersection 8, the latter limited to measurements of total cross-section. They found that the total cross-section rises with energy after passing through a broad minimum near 100 GeV equivalent laboratory energy. The total cross-section, in fact, was found to rise by about 10 % over the ISR

¹⁵⁶ Actually, two other experiments can be classified in this category: R102, designed by a Saclay–Strasbourg Collaboration, aimed at studying interactions producing gamma rays and electrons with large transverse momentum; R204, designed by a collaboration of British Universities, aimed at detecting muons with large transverse momentum as a search for intermediate vector boson. The latter did not give any significant result; the former contributed to the discovery of large transverse momentum phenomena, as we shall see in the following.

¹⁵⁷ L. Di Lella, interview with J. Krige and A. Russo, 29/8/90.

¹⁵⁸ The total cross-section is a measure of the probability that two protons interact anyhow, elastic scattering is the process by which the interaction between the two particles is just a rebound against each other like between two billiard-balls.

energy range and this came as a surprise as data obtained at lower energies seemed to indicate a constant asymptotic value (fig. 14).¹⁵⁹

The second important discovery was the surprisingly copious production of pions with large transverse momentum (p_T), with cross-sections many orders of magnitude greater than had been empirically predicted on the basis of pre-ISR data. The transverse momentum is the momentum component in the direction perpendicular to that of colliding protons and lower-energy experiments had shown that inclusive pion production, i.e. interactions like

$$p + p \rightarrow \pi + X$$

where X is anything else produced in the interaction, presented cross-sections rapidly decreasing with the transverse momentum of the pion. The transverse momentum distribution, in fact, fell exponentially fast, with a mean value of 0.35 GeV/c. Evidence for a marked departure from this exponential fall-off was observed by three groups at the ISR in 1972 (R102, R103, R203), whose results were published in 1973.¹⁶⁰ Departure from the expected exponential behavior was already evident at 1 GeV/c and became orders of magnitude greater than the extrapolated value at higher p_T (fig. 15).

The excess production of large- p_T hadrons in high energy pp interactions was indeed the most important discovery of ISR physics. It was immediately interpreted as the evidence of partons also in strong interactions and prompted a distinctive tradition of hard hadron scattering experiments to investigate large transverse momentum hadronic processes both at the ISR and, later, at Fermilab and the CERN SPS.¹⁶¹

Quite paradoxically, the important discovery which gave the ISR a ticket to enter the new territories of hard-scattering particle physics also brought to light its intrinsic weakness. Two aspects are relevant in this respect, the first related to the study of large- p_T hadron production in hadron interactions, the other related to lepton physics.

¹⁵⁹ Amaldi *et al.* (1973), Amendolia *et al.* (1973 a), Amendolia *et al.* (1973 b). A review of ISR results on the total cross section is in Amaldi & Schubert (1979) or (1980). A review on total cross section results is Giacomelli (1976).

¹⁶⁰ Banner *et al.* (1973), Büsser *et al.* (1973), Alper *et al.* (1973).

¹⁶¹ Jacob & Landshoff (1978) and Darriulat (1980).

With regards to the first aspect we must consider the physical interpretation of large- p_T phenomena in the quark-parton, hard-scattering model (fig. 16).¹⁶² According to this picture, an observed large- p_T particle should be considered as a member of a jet of hadrons strongly collimated in the direction towards the trigger detector with an associated jet somewhere in the other direction. It was an obvious consequence to design experiments aimed at analysing the structure of final states of large- p_T processes. The key point was to study the correlations among large- p_T particles but instrumentation at the ISR was inadequate to make such correlation studies. These, in fact, required complex detector arrays surrounding the interaction region and sophisticated electronic triggers in order to pick out interesting events in the typical large background of hadronic interactions.

We should recall that the SFM had been specifically conceived to study events producing secondary particles at small angles and, in the words of an experimenter, for large angle events, "the SFM was like a nightmare."¹⁶³ At large angles, in fact, the magnetic field was very weak (actually zero at 90°) and with rapidly changing directions. It thus required a long and patient effort to develop highly sophisticated detecting systems and software for track reconstruction in order to study large- p_T events. By 1975, the problems and limitations of the SFM were quite evident and a proposal was also suggested to rotate the magnets by 90° . A working group was formed to study this proposal and then, "after considerable discussion", the proposal was rejected but a programme for upgrading the facility was eventually implemented.¹⁶⁴

¹⁶² This hard-scattering model (Berman *et al.* (1971), Ellis & Kislinger (1974), Field & Feynman (1977)) is what eventually proved to be correct. Other models were proposed by 1973 but were discarded when more data became available: see Sivers *et al.* (1976).

¹⁶³ G. Goggi, interview with the author, 11/4/91.

¹⁶⁴ A discussion on the SFM was held at the 58th meeting of the SFM (11/7/75), CERN/ISRC/75-23, 14/7/75. The proposal to rotate the magnet in order to transform the SFM into "a powerful electron detector" was suggested by a Bologna-CERN collaboration led by A. Zichichi and was presented in CERN/ISRC/74-53, **date**, and CERN/ISRC/75-3, 31/1/75. The setting up of the working group, co-ordinated by F. Muller, was decided at the 56th meeting of the ISRC (25/4/75), CERN/ISRC/75-17, 28/4/75 and its results were discussed at the 59th meeting of the ISRC (10/9/75), CERN/ISRC/75-35, 11/9/75.

The need of big detectors

In spite of difficulties, from 1973 to 1976, a long series of correlation studies at the ISR provided good evidence of the validity of the hard-scattering model and contributed important results.¹⁶⁵ A significant development, however, was only possible by the use of hadron calorimeters to trigger on the energy of a whole jet rather than on a single large p_T particle. From an analysis of the ISR correlation data, in fact, it was predicted that, for a given value of the transverse momentum, the triggering rate with a suitable calorimeter should be some two orders of magnitude greater than with a single particle.¹⁶⁶

It took a long time to implement calorimeter experiments at the ISR, however. This was due not only to a certain "conservative mode" of the ISR Committee (remember the rejection of Rubbia's proposal in 1972–73) but also to intrinsic technical difficulties:

At the ISR [...] the implementation of a jet trigger is a difficult experimental problem. Hadron calorimeters have lower performance at smaller energies. Systems having the same transverse momenta have much larger laboratory energies at Fermilab than at the ISR. In addition none of the existing ISR detectors could conveniently accommodate such a calorimeter.¹⁶⁷

It was at Fermilab that the first calorimeter experiments were performed which permitted a more detailed analysis of jet production.¹⁶⁸ The first ISR calorimeter detector optimized for large- p_T hadron events came into use only in 1980 (experiment R807), as a part of the Axial Field Spectrometer (AFS) facility. By

¹⁶⁵ For a review and references see Jacob & Landshoff (1978), Darriulat (1980). A review of knowledge about large transverse momentum phenomena by 1976 is Ellis & Stroyanowski (1977).

¹⁶⁶ Jacob & Landshoff (1978), p. 292. About calorimeters see Fabjan & Ludlam (1982). It must be stressed that much cleaner data on jet production could be obtained by e^+e^- annihilation experiments (fig. 19). The first significant result in this respect came in 1975 from the SPEAR facility at SLAC: Hanson *et al.* (1975). The start of operation of the new e^+e^- colliders PETRA at DESY (1978) and PEP at SLAC (1980) opened up the possibility of performing experiments at much larger energies.

¹⁶⁷ Darriulat (1980), p. 166.

¹⁶⁸ Bromberg *et al.* (1977); Bromberg *et al.* (1978).

the time the ISR started to give interesting results with this new facility, however, more spectacular results were already being obtained by the SPS pp^- collider.

The second aspect, as we have mentioned, regards the use of the ISR for lepton physics. One of the groups which discovered the large high- p_T hadron production was the CERN–Columbia–Rockefeller (CCR) Collaboration of the dilepton experiment R103. As we have remarked, the detectors for leptons had been placed at large angles where, due to the known exponentially falling p_T -dependence, the hadron background was expected to be small and relatively easy to cope with. The discovery that this was not the case represented, of course, a setback for this kind of investigation. The reaction was along two lines: on the one hand to improve the existing apparatus in order to investigate the new phenomenon while still keeping the original aim of the experiment; on the other hand, to propose a new experiment with more sophisticated, wide-angle lepton detectors.

On the first line the CCR Collaboration joined the group from Saclay which ran experiment R102 in the same intersection I-1. The calorimeter of R102 was added to the detectors of R103 forming the new experiment R105 which started taking data in February 1973.¹⁶⁹ On the second line, a proposal to continue with increased sensitivity the search for electrons, together with large- p_T hadrons, was presented in early 1973 by the CCR Collaboration which a group from Oxford joined in 1974.¹⁷⁰ It was based on a superconducting solenoid magnet providing a field along the proton beams, a configuration particularly suited to study the production of particles at large angles with azimuthal symmetry. At its 39th meeting, in July 1973, the ISR Committee expressed "its interest in the physics of this experiment and agreed that lepton physics at the ISR should receive emphasis."¹⁷¹ The Committee recommended studies on the effect of this solenoid on the ISR and on prototype detectors and approved the proposal in March 1974

¹⁶⁹ CERN/ISRC/72-13, **date**, with Add. 1, **date**, and Add. 2, **date**. A proposal to study large transverse momentum phenomena was first suggested by the Saclay group and was approved by the ISRC as experiment R105 at its 31st meeting (23/8/72), CERN/ISRC/72-25, 24/8/72. Then, in November, a joint proposal was presented by Saclay and the CCR Collaboration and was approved by the ISRC in January 1973 (34th meeting, CERN/ISRC/73-4, 25/1/73).

¹⁷⁰ CERN/ISRC/73-13, **date**, Add. 1, **date**, Add. 2 (CERN/ISRC/74-5), **date**.

¹⁷¹ ISRC, 39th meeting (10/7/73), CERN/ISRC/73-22, 11/7/73, p. 3.

as experiment R108.¹⁷² After more than three years of building and testing, the experiment started to operate in 1977 and gave its first significant results in 1978.¹⁷³

By that time other sophisticated, wide-aperture magnet detectors were also operative for lepton pair studies: in particular the toroid spectrometer R209 to study muon pair production and the "lampshade magnet" detector R606 to study electron pair production. The former originated from a proposal presented in 1973 by S. Ting on behalf of a Genova-Harvard-MIT-Pisa Collaboration.¹⁷⁴ The experiment was originally approved for installation at intersection I-8 (experiment R804) by 1975 but, due to scheduling problems, its installation was delayed until 1976 when it was decided to move it to intersection I-2.¹⁷⁵ The latter originated from a proposal to improve the experiment R605 run by an Aachen-CERN-Harvard-Munich-Riverside collaboration led by C. Rubbia.¹⁷⁶

In 1978 the upgrading of the SFM was also completed, with two experiments, R415 and R416, taking data on electron pair production. The first derived from a proposal of Zichichi's CERN-Bologna collaboration; the second had been proposed by a CERN-Collège de France-Heidelberg-Karlsruhe collaboration joined eventually by groups from Annecy (LAPP) and Warsaw. In this case too, it took a long time for the ISR Committee to discuss and approve the two experiments together with the upgrading of the SFM.¹⁷⁷

At last the ISR was well equipped with a set of powerful wide angle detectors. It was too late.

¹⁷² ISRC, 46th meeting (26/3/74), CERN/ISRC/74-18, 28/3/74.

¹⁷³ Angelis *et al.* (1978) and (1979).

¹⁷⁴ CERN/ISRC/73-28, **date**, and Add. 1, **date**. ISRC, 42nd meeting (20/11/73), CERN/ISRC/73-35, 22/11/73.

¹⁷⁵ ISRC, 65th meeting (5/5/76), CERN/ISRC/76-16, 6/5/76.

¹⁷⁶ CERN/ISRC/75-33, **date**, CERN/ISRC/75-42, **date**, CERN/ISRC/75-43, **date**. In the following, groups from Holland and from Northwestern University joined the collaboration.

¹⁷⁷ The R415 proposal is in CERN/ISRC/74-53, **date**, CERN/ISRC/75-3, 31/1/75, and CERN/ISRC/76-13, **date**. The R416 proposal is in CERN/75-41, **date**. They were approved by the ISRC at its 65th meeting (5/5/76), CERN/ISRC/76-16, 6/5/76. Status reports on the first phase of data taking are CERN/ISRC/78-12, **date**, and CERN/ISRC/78-11, **date**, respectively.

A difficult period

The specific features of the ISR and the dramatic discovery that there was a lot of hadronic physics going on at large angles had posed the problem of building a new generation of detectors at the very beginning of ISR operation. On the one hand it was recognised that the whole angular region around the intersection was worth investigating; on the other hand, more sophisticated and selective triggering systems were required in order to discriminate among different kinds of events. Whether because of technical and financial difficulties or to the slowness of most CERN physicists to tune their practice to the new trends of particle physics, it took a rather long time, as we have seen, to build the new experimental facilities which were needed. One must also remark that, at that time, large electronic detectors were slowly taking the lead over bubble chambers in experimental particle physics and, in the words of an ISR experimenter, "people did not think as big in those days."¹⁷⁸ From 1974 to 1977, according to M. Jacob, it was a somewhat difficult period at the ISR:

One had to make do with existing devices (combining spectrometers or spectrometers and hodoscopes) exploiting particularly the SFM, which eventually became a powerful, though not ideal, instrument only by means of a long and patient effort at both the hardware and software levels.¹⁷⁹

This period, continued Jacob, "was marked at both ends by the two setbacks of leaving the discovery of the J/ψ (1974) and the discovery of the Y (1977) to other laboratories".

The news of the discovery of the J/ψ caused much frustration among CERN physicists.¹⁸⁰ In fact, Di Lella and Lederman's CERN–Columbia–Rockefeller collaboration of experiment R103 had the same objectives as Ting's and they had caught the beginning of the very narrow peak of the J/ψ . Due to the unexpected high hadronic background which saturated their data acquisition system, they had

¹⁷⁸ Interview of L. Camilleri with J. Krige, 10/9/90. I wish to thank J. Krige and L. Camilleri for allowing me to use the tape record of this interview.

¹⁷⁹ Jacob (1984), p. 35.

¹⁸⁰ Taubes (1989), p. 25–26, gives a rather vivid description, with no documentation though, of this frustration.

to put the threshold of their detecting apparatus just above what proved to be the mass value of the J/ψ (3.1 GeV against 3.097 GeV) and then missed the discovery by a few thousandths of GeV.¹⁸¹ In the event, after the announcement of the discovery of the J/ψ , the CERN–Columbia–Rockefeller–Saclay Collaboration of experiment 105 adjusted its detectors and quickly observed a few J/ψ events.¹⁸²

Just one month after the announcement of the discovery of the J/ψ , a rather nervous meeting of the ISR Committee was held, where a host of proposals to search for the new charmed particles was discussed.¹⁸³ The CERN–Columbia–Oxford–Rockefeller Collaboration urged a new scheduling for their superconducting solenoid (R108) and presented as well a new proposal for a search for high mass states decaying into two electrons.¹⁸⁴ A proposal to search for charmed particles was also presented by a CERN–Saclay collaboration and, "in the discussion following these presentations, mention was made of the use of the SFM facility as a muon spectrometer and the possibilities of using it as an electron detector."¹⁸⁵ The ISR Committee recommended the CERN–Saclay proposal as experiment R702 and this, in due time, obtained beautiful data on the J/ψ and related phenomena.

At the same meeting, Zichichi's Bologna–CERN collaboration presented its proposal "to transform the SFM into a powerful electron detector", which eventually considered also the possibility of rotating the whole magnet by 90°. ¹⁸⁶ As we have already said, this proposal was rejected and a project to upgrade the SFM was started instead.

In spite of the strong engagement in lepton searches at the ISR since 1975, this kind of investigation kept being hampered by the large- p_T hadronic background

¹⁸¹ Di Lella (1984) and interview with A. Russo and J. Krige, 29/8/90. See Büsser *et al.* (1974).

¹⁸² Büsser *et al.* (1975).

¹⁸³ ISRC, 53th meeting (11/12/74), CERN/ISRC/74–59, 12/12/74. Other proposals were also presented at the following meeting.

¹⁸⁴ CERN/ISRC/74–54, **date [check]** and CERN/ISRC/74–56, 25/11/74.

¹⁸⁵ ISRC, 53rd meeting (11/12/74), CERN/ISRC/74–59, 12/12/74, p. 1. The CERN–Saclay proposal is in CERN/ISRC/74–51, **date**, and CERN/ISRC/74–55, **date**. A group from Zurich eventually joined the collaboration.

¹⁸⁶ CERN/ISRC/74–53, **date**, and CERN/ISRC/75–3, 31/1/75. Zichichi's proposal was presented by T. Massam and discussed at the open session of the following ISRC meeting (19/2/75), CERN/ISRC/75–10, 20/2/75.

and by the very low cross-sections of these processes. In fact, in comparison with experiments at fixed target accelerators, collider physics suffered two major difficulties regarding lepton pair studies: the relatively low luminosity and the very wide solid-angle spread over which lepton pair production may occur. On standard accelerators, they are concentrated forwards by the motion of the centre-of-mass. Lacking sophisticated detectors surrounding the interaction point, the ISR could not compete with Fermilab and then with the CERN's SPS. And it was at Fermilab, in fact, that Lederman discovered the Y particle was, his revenge after missing the J/ψ at Brookhaven and at the ISR.¹⁸⁷ Even when the discovery had been announced, it took several months to collect evidence for this particle at the ISR, in spite of the fact that the cross-section for Y production at the ISR turned out to be two orders of magnitude larger than at Fermilab.

By 1976–1977, "physics at the ISR [had] lost much of its past glamour to many," as Jacob put it.¹⁸⁸ The new detectors were still under construction and the start of the SPS was offering a very tempting alternative. In that period there were more and more rumours at CERN about the eventual decision to close the ISR in order to free resources to exploit better the new 300 GeV proton synchrotron and to build a new accelerator. As early as in October 1975, in fact, a confidential "Note for discussion on the long-term future of CERN" was sent by J.B. Adams to members of the future Directorate of CERN. Here, after discussing the financial boundary conditions of the Laboratories, it was stated that, in order to start a new major project in the 1980s, the ISR had to be closed down about 1980.¹⁸⁹ Opinions on this question were split, of course, but the uncertainty about the future of the ISR certainly did not help those who advocated the need to exploit the machine in the best way.

In 1976 and 1977 a two-session *Workshop on future ISR physics* was held which bears witness to these difficulties even though it was acknowledged that the installation of the new detectors, the rise in luminosity to be obtained by the insertion of superconducting low- β sections, and the possible use of antiprotons might produce a significant improvement of the experimental programme. The

¹⁸⁷ Herb *et al.* (1977).

¹⁸⁸ Jacob (1984), p. 35.

¹⁸⁹ A copy of this document, coded Lab II-DI/JBA/pd and dated 23/10/75, can be found among Johnsen's papers in the ISR Archive at CERN.

possibilities of associating the ISR to the SPS and of upgrading the ISR in energy by the introduction of superconducting magnets were also suggested and discussed.¹⁹⁰ After the workshop there was, in fact, a new surge of scientific interest in ISR physics but everybody knew that the ISR's were probably numbered.

The last achievements

The latter period of the ISR (1978–1983) was not devoid of important results. The availability of proper detectors finally gave the possibility of exploiting fully the information contained in the events produced by the collisions and the machine kept proving to be a wonderful tool for experimenting. By the insertion of superconducting low- β sections at intersection I–8, the maximum luminosity grew dramatically to over $10^{32} \text{ cm}^{-2} \text{ sec}^{-2}$ and this allowed the best use of the axial field magnet detector. The improvement of the vacuum and the highly sophisticated control system gave physicists working at the rings extremely stable beams for their experiments and very long uninterrupted physics run could be provided, of 50–60 hours if desired, with a very high fraction of stable operation.¹⁹¹ The versatility of the ISR also showed itself when it was decided to use it to store other kinds of particles. Antiprotons, deuterons and α particles were successfully stored in the rings and the results of experiments performed with these particles complemented those obtained by pp collisions with regard to global features of hadronic interactions.¹⁹² Finally, the continuing progress of research in accelerator physics which was made possible at the ISR, in particular the development of the technique of stochastic cooling on anti-protons, provided invaluable knowledge for the implementation of the SPS pp- Collider and the LEP.

¹⁹⁰ The conclusions of the two sessions of the ISR workshops are reviewed by B.G. Pope and by M. Jacob, respectively, in CERN/ISRC/76–32, 2/11/76 and in CERN/ISRC/77–20, 26/9/77. These and other documents related to this workshop are in file DGE 21561. The conclusions of the workshop were discussed at open meetings of the ISRC: 68th meeting (15/10/76), 18/10/76, and 74th meeting (21–22/9/77), 23/9/77.

¹⁹¹ Johnsen (1984).

¹⁹² Faessler (1984), Camilleri (1987).

Among the achievements of the last period of operation of the ISR one must recall the results on jet production, where useful data were obtained which complemented those being obtained at the SPS Collider, the study of charmed hadrons and the investigation of charmonium states. The most important result, however, was the discovery of prompt photons at large transverse momentum. The emission of single energetic photons at large p_T in hard proton–proton collisions had been theoretically anticipated within the framework of quantum chromodynamics. As the photon can emerge without interacting further, unlike quarks or gluons which give rise to jets, it provides a window through which one can get direct information about the primary scattering of proton constituents. The results obtained in 1979–1980 by experiments R806 and R108 confirmed the validity of the theory and represented an important *première* at the ISR.¹⁹³ Experiments on this topic then continued at intersection I–8 with experiment R808 and at intersection I–1 with experiment R110. Correlations between single-photon events and associated charged secondaries were studied by experiments R806 and R807.

Epilogue

The end of the ISR came on 23 December 1983 at 6.30 a.m., when the last two beams of protons were dumped. The machine was working satisfactorily and still providing good results within an active physics programme. In fact, the ISR had to be closed down in order to free resources to be used for CERN's new undertakings and this justified a premature termination which, in some cases, left a "half-finished job".¹⁹⁴

Some sweet and sour notes, which revealed physicists' mixed feelings about the ISR, could be heard at the two meetings that were "the formal end of a glorious chapter of CERN history".¹⁹⁵ These were the last meeting of the ISR

¹⁹³ Diakonou *et al.* (1979) and (1980), Angelis *et al.* (1980). Pioneering work on direct single-photon production had been done by experiment R107.

¹⁹⁴ Jacob (1984), p. 36.

¹⁹⁵ CERN's Director General H. Schopper at the last meeting of the ISRC, cited in G. Bellettini's preface to Jacob & Johnsen (1984), p. vi.

Committee, on 27 January 1984, and the official closure ceremony of the machine, five months later. At the former meeting, M. Jacob wanted to put as an epigraph to his review of the ISR physics the first lines of Mark Antony's famous funeral oration from Shakespeare's Julius Caesar:

I come to bury Caesar not to praise him;
The evil that men do lives after them,
The good is oft interred with their bones;
So let it be with Caesar.¹⁹⁶

The evil of the ISR was, of course, the missed discovery of the "two gems of physics in the seventies", namely the J/ψ and the Y . "Physics at the ISR", remarked Jacob, "is, in many people's mind, marred by this shortcoming with lepton pairs, and this had to be mentioned first as an evil that lives on long after." The bright results which actually originated from experiments at the ISR, the "good" of the machine, inevitably remained in the shadow of this setback and were almost forgotten as such as they became part of the general background in particle physics. And for the development of particle physics the ISR had to die, killed like Caesar, because, as Brutus reminded his fellow-citizens,

Not that I loved Caesar less,
But that I loved Rome more.¹⁹⁷

Shakespeare's verses echoed also at the closure ceremony of the ISR, on 26 June 1984. Here, CERN's Director General H. Schopper wanted to stress that he had come "to bury the ISR *and* to praise it." The funeral, in his words, "should not be too sad, since the deceased has had a very glorious life."¹⁹⁸ After him, V. Weisskopf, a long time supporter of the ISR and probably the main person responsible for its approval in 1965, preferred to claim that he had come "to praise ISR *and to leave it to others to bury it*." The former Director General went on arguing that, to the "famous question" of the missed discovery of the J/ψ and of the Y , one had but to answer:

¹⁹⁶ Jacob (1984), p. 24–25.

¹⁹⁷ Jacob (1984), p. 74.

¹⁹⁸ H. Schopper in *Closure Ceremony of the Intersecting Storage Rings, 26/6/1984*, CERN, January 1985, p. 2, underlined in the original text.

It can be explained as being due to the fact that one had to develop the necessary instrumentation and this has taken much time. It is too bad, and we have probably missed one or two Nobel prizes, but let me say one thing. Does it really matter so much? If the J/psi and the upsilon [had] been discovered here, it would not have changed the landscape of high energy physics: it is not so important where it is discovered. The really important thing about the ISR is its success as an instrument, because *that fact did change the landscape of high energy physics*.¹⁹⁹

This is hard to take at face value. As a matter of fact, physicists do value the who and where of important discoveries. With less rhetoric, the last chairman of the ISR Committee, G. Bellettini, acknowledged that

Although one might admit that no specific discovery of historical importance was made here, still our views of the behaviour of strong interactions at high energies have changed qualitatively because of the work done at the ISR – and this is of historical importance.²⁰⁰

This is probably the most that can be said for the physics done at the ISR.

At both meetings, Johnsen's was the only triumphant note. The ISR project, in the words of its builder, "started as accelerator research [and] it continued as accelerator research" and the ISR "has continually carried out an accelerator physics programme which also got high priority on the machine and really paid off handsomely."²⁰¹ After listing the long series of results obtained at the ISR, Johnsen concluded:

[The ISR] has been about the finest instrument one can imagine for research in accelerator physics. [...] Before the ISR, everyone talked about fixed-target machines, but nowadays it is essentially on the colliders that people base their hopes for the future. This is really a fantastic development for those of us who remember the reluctance of

¹⁹⁹ *Closure Ceremony*, p. 5 and 7, underlined in the original text.

²⁰⁰ *Closure Ceremony*, p. 14.

²⁰¹ *Closure Ceremony*, p. 11. Accelerator physics at the ISR is reviewed in Johnsen (1984) and (1986).

many to accept the idea of colliders as a physics tool before the ISR was launched.²⁰²

He was right, we believe. Even the most severe critics of the ISR had to acknowledge the splendid performance of the machine and its crucial contribution to CERN's glamorous achievements with the SPS Collider and the LEP. This is the real historical value of the ISR, at least for CERN.

The ISR is no longer there: unlike its predecessors, the proton-synchrotron which is still in operation and the cyclotron which was closed only in 1991, the ISR has been completely dismantled and only a large annular hillock in the French part of CERN's site marks the place of the tunnel where the hundreds of magnets, detectors and other apparatus of the machine and of its experiments had been busily working for 13 years. Physicists always tend to forget their past: each step of evolution of their discipline is considered by them as a new starting point from which previously acquired knowledge must be used without any consideration of how and why it was obtained. So it is for the ISR. Physicists did not love the ISR and, due to technical difficulties or to lack of imagination, they were not able to get important discoveries from it. Its good results soon became a part of the new general framework of particle physics in the 1980s while the machine as such has remained the one that missed the J/ψ and the Y . "Exploit technique, physique pauvre", is the judgement of a particle physicist who liked to write a history of his discipline:

Prouesse technique, modèle pour projects ultérieurs, les ISR ont été une machine d'ingénieurs plutôt que de physiciens. En ce sens ils sont un exemple frappant de la croissance du poids des ingénieurs et des appareils techniques des grands laboratoires dans le développement de la physique des particules.²⁰³

This is, in a certain sense, the ISR paradox. Its construction was strongly advocated by the engineers as a technical challenge but was eventually suffered by most physicists as an unfortunate compromise. It did prove to be an unfortunate choice from the point of view of physics but, in the light of following developments, it was a good fortune for CERN to have built it as it proved to be a

²⁰² *Closure Ceremony*, p. 13.

²⁰³ Crozon (1987), p. 204.

necessary technical step in the path that was to lead to the following successful CERN colliders, the SPS pp- Collider and the LEP. It depends on personal feelings and experience whether one prefers to stress the good or the evil of the ISR.

TABLE 1

Main parameters of the ISR

Physical parameters

Design luminosity	$4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
Design current per ring	20 A
Maximum energy of each ring	31.4 GeV

Geometrical parameters

Circumference of rings	942.66 m
Average radius of equilibrium orbit	150.03 m
Maximum distance between inner and outer arc	8.79 m
Intersection angle	14.77°
Straight section at intersection region	16.78 m
Difference in beam level between ISR and PS	11.80 m

Beam parameters

Number of magnet periods	48
Number of superperiods	4
Stack width for 2.5 % momentum spread	$\approx 50 \text{ mm}$
Maximum height of beam profile	$\approx 15 \text{ mm}$
Horizontal close orbit distortions after correction	$\approx 6 \text{ mm}$
Vertical close orbit distortions after correction	$\approx 4 \text{ mm}$

Magnet parameters (one ring)

Field at equilibrium orbit (28 GeV/c)	12 kG
Maximum current to magnet coils	3750 A
Maximum power dissipation	6.8 MW
Total steel weight in blocks	4350 ton
Total copper weight	560 ton

R.F. system (one ring)

Number of R.F. cavities	7
Harmonic number	30
Centre frequency (25 GeV/c)	9.53 MHz
Maximum peak RF voltage per turn	20 kV
Minimum defined RF voltage per turn	50 V

Vacuum system (one ring)

Pressure	10^{-11} to 10^{-12} torr
Vacuum chamber material	low carbon stainless steel
Vacuum chamber magnetic permeability	< 1.005
Length of vacuum chamber	$\approx 1 \text{ km}$
Dimensions of elliptical chamber in magnets	$160 \times 52 \text{ mm}^2$
Diameter of circular chamber in intersections	160 mm
Number of roughing pump stations	35
Number of sputter ion pumps	144
Number of titanium sublimation pumps	250
Number of Bayard-Alpert gauges	250

TABLE 2
Operation of the ISR for colliding beam physics in 1973

<i>Momentum</i> GeV/c	<i>Running time</i> percent	<i>Beam Current Range</i> Amperes	<i>Luminosity</i>	
			Maximum $\times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$	Average
11.8	12.8	4 - 6	0.68	0.4
15.3	17.8	5 - 8	1.25	0.6
22.5	21.8	8 - 14	4	1.8
26.5	31.5	8 - 14	4.5	2
31.4	6.8	3 - 5	0.36	0.15
Different in each ring	9.3	various	various	

[From ISR (1974), p. 26]

TABLE 3
Staff of the ISR Division at the end of each year of the construction period *

	1965	1966	1967	1968	1969	1970
Staff	88	162	216	284	313	320

(*) From CERN Annual Reports 1966–1970

TABLE 4

Breakdown of annual costs for the construction of the ISR, compared with original estimates *
(in units of million Swiss francs)

	1966	1967	1968	1969	1970	1971	Total
Estimates (at 1965 prices)	21.7	68.6	73.3	74.6	67.1	26.7	332.0
Expenditure (at 1965 prices)	20.3	66.0	72.4	78.6	68.2	20.1	325.6
Actual expenditures	21.1	71.1	79.8	88.9	81.4	25.0	367.3

(*) From CERN/FC/1572, 2/5/73. Estimates as in CERN/613, 25/11/65.

TABLE 5

Breakdown of ISR Costs Compared With Original Estimates*
(in units of million Swiss francs at 1965 prices)

Item or Group	Actual Costs	1965-66 Estimates
Staff Expenses	35.6	35.0
General Expenses	5.4	4.6
Installation Labour	-. - +	13.0
General Overheads	25.1	25.0
Direction and General Services	2.3	1.5
General Layout (plant and buildings)	102.2	97.0
Magnet	47.1	66.5
Magnet Power Supply	5.4	9.1
RF and Beam Observation	7.4	7.0
Vacuum	27.3	28.9
Beam Transfer	22.3	14.7
General Engineering	12.2	8.1
Survey	0.7	0.5
Controls	20.7	10.5
Preparations for ISR Experiments	11.6	10.6
General Studies Group	0.3	-. -
TOTALS	325.6	332.0

(*) From CERN/FC/1572, 2/5/73.

(+) 7.9 MSF for installation labour is included in the actual costs for the various groups (mostly the Controls Group).

TABLE 6

THE ISR PARAMETER COMMITTEE
(Group leaders and consultants)

K. Johnsen	Director of the ISR Department
C.J. Zilverschoon	Deputy Director
W. Schnell	Radio frequency and running-in
G. Schaffer	Controls and computers
L. Resegotti	Magnets
B. de Raad	Beam transport and injection
S. Van der Meer	Power supply
F. Bonaudi	General layout and civil engineering
E. Fisher	Vacuum
E. Keil	Theoretical studies
J. Gervaise	Survey and setting of magnets
H. Horisberger	Technical engineering and installation
M.H. Blewett	Secretary, administration, budgets and planning
H.G. Hereward	Special consultant on accelerator problems

Fig. 2

Cross-section of the ISR beam-pipe in the magnet gap. In order to produce a highly uniform magnetic field, the distance between the pole pieces was made smaller than their width. This leads to a flat chamber and, consequently, to stacking in the horizontal plane. The small cross indicates the injection orbit and the area available for stacking accumulation is shaded.

[From Hübner (1977), p. 8]

This schedule is definitive at time of publication. For later changes see

Eng.-in-Charge SRC.

ISR Run		595		596		597		598		599		600					
E ₁ /E ₂ GeV				26/26 SFM		31/31 SFM		26/26 SFM		26/26 SFM							
Intensity I 1				22 A		10 A		5A	24 A	24 A							
I 2				22 A		10 A		5A	24 A	24 A							
Injection				206 1/2		206 1/2		206 1/2		206 1/2							
Date	MON 12/5		TUE 13/5		WED 14/5		THU 15/5		FRI 16/5		SAT 17/5		SUN 18/5		MON 19/5		
Time	06.00 08.00		09.00 11.00 17.00		08.00 15.00 22.00		09.00 11.00 13.30 14.30 17.00		07.30 09.00 11.00 15.00				07.00 08.00 09.00				
Operation			MD		SU	PH	*	SU		PH		SU		PH		MD	MD
I 1 R107	TUNNEL OPEN SEARCH																
I 2 R205 206																	
I 4 R406																	
I 6 R605																	
I 7 R702																	
I 8 R805 R806T																	
Access to ISR Tunnel		X	X X	C	X	X X	C	X		X X X X	C	X	X	X X	X	C	X

MD = Machine Development

SU = Setting Up for Physics

PH = Physics

M = Experimental Magnet Tests

X = No access. Ti = Ti ball evaporation. H₂ = Hydrogen leak.

C = Controlled access (for details see Eng.-in-Charge SRC)

S = Beam Steering. L = Luminosity measurement. R = Radial adjustment.

* THE RUN WILL CONTINUE IF A LONG CONTROLLED ACCESS IS NOT NEEDED.

Fig. 3 - ISR operation in May 1975

(From EWDS 22321)

Fig. 4 - CERN proton-synchrotron and the ISR as presented in the original project, ISR (1964), fig. II.1

Fig. 5 - The final configuration of the ISR with the beam transfer channels from the PS to the rings and to West Hall (on the left). The experimental halls at intersections I-1 and I-4 are also visible.

From Keil (1972), p. 15.

Fig. 6 - The average pressure of the ISR vacuum for the years 1971-1983. From Johnsen (1984), p. 9.

Fig. 7 - Maximum ISR luminosity during physics runs. One can see the dramatic effect of the insertions of low- β sections at intersections I-1 and I-8, the latter with superconducting quadrupoles.

From Johnsen (1984), p. 18.

Fig. 8 - Deep inelastic scattering in the Bjorken-Feynman parton model.

Fig. 9 - Neutrino-proton scattering in the quark-parton model.

Fig. 10 - Lepton-pair production in the quark-parton model.

Fig. 11 - Electron-positron annihilation to hadrons in the quark-parton model.

(a) Plan view

(b) Side view

Fig. 12

Schematic diagram of the experimental set-up of Ting's experiment in which the J particle was discovered. M_0 , M_1 and M_2 are dipole magnets; A_0 , A, B and C are 8000-wire proportional chambers; a and b are each 8×8 hodoscopes; S designates three banks of lead-glass and shower counters; C_b , C_0 and C_e are gas Cherenkov counters.

From Ting (1977), p. 239

Fig. 13

Schematic diagram of the magnetic detector Mark I at SPEAR

From Schwitters & Strauch (1976), p. 125.

Fig. 14

Total cross section measurements by 1972

(From CERN Annual Report 1972, p. 13)

a

b

Fig. 15 - Pion production with large transverse momentum in p-p collisions as reported by:
 a) Banner et al. (1973) and
 b) Büsser et al. (1973).

Fig. 16

The quark-parton model visualized in three different high-energy processes: (a) lepton-hadron interaction; (b) e^+e^- annihilation; (c) hard-scattering hadron-hadron collision. In the latter case it is assumed that constituents a and b of the two colliding hadrons scatter into constituents c and d which result in hadron jets at wide angle. The observed large p_T particle h is a member of a jet.

From Field and Feynman (1977), p. 2591 (with minor modification)

BIBLIOGRAPHY

Abrams *et al.* (1974)

G.S. Abrams, D. Briggs, W. Chinowsky, C.E. Friedberg, G. Goldhaber, R.J. Hollebeek, J.A. Kadyk, A. Litke, B. Lulu, F. Pierre, B. Sadoulet, G.H. Trilling, J.S. Whitaker, J. Wiss, J.E. Zipse, J.-E. Augustin, A.M. Boyarsky, M. Breidenbach, F. Bulos, G.J. Feldman, G.E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie, R.R. Larsen, V. Lüth, H.L. Lynch, D. Lyon, C.C. Morehouse, J.M. Paterson, M.L. Perl, B. Richter, P. Rapidis, R.F. Schwitters, W.M. Tanenbaum, F. Vannucci, "Discovery of a second narrow resonance in e^+e^- annihilation", *Physical Review Letters*, **33** (1974), 1453–1455.

Albrow (1983)

M. Albrow, "Protons in collision", *New Scientists*, 8 December 1983, 743–745.

Alper *et al.* (1973)

B. Alper, H. Boggild, G. Jarlskog, G. Lynch, J.M. Weiss, P. Booth, J.L. Carroll, J.N. Jackson, M. Prentice, G. Von Dardel, L. Jonsson, G. Damgaard, K.H. Hansen, E. Lohse, F. Bulos, L. Leistam, A. Klovning, E. Lillethun, B. Duff, F. Heymann, D. Quarrie, "Production of high transverse momentum particles in p–p collisions in the central region at the CERN ISR", *Physics Letters*, **44B** (1973), 521–529.

Altarelli (1982)

G. Altarelli, "Partons in quantum chromodynamics", *Physics Reports*, **81** (1982), 1–129.

Amaldi *et al.* (1973)

U. Amaldi, R. Biancastelli, C. Bosio, G. Matthiae, J.V. Allaby, W. Bartel, G. Cocconi, A.N. Diddens, R.W. Dobinson, A.M. Wetherell, "The energy dependence of the proton–proton total cross–section for centre–of–mass energies between 23 and 53 GeV", *Physics Letters*, **44B** (1973), 112–118.

Amaldi & Schubert (1979) or (1980)

U. Amaldi, K. Schubert, "...", *Nuclear Physics B*, 1979 or 1980.

Amendolia *et al.* (1973 a)

S.R. Amendolia, G. Bellettini, P.L. Braccini, C. Bradaschia, R. Castaldi, V. Cavasinni, C. Cerri, T. Del Prete, L. Foà, P. Giromini, P. Laurelli, A. Menzione, L. Ristori, G. Sanguinetti, M. Valdata, G. Finocchiaro, P. Grannis, D. Green, R. Mustard, R. Thun, "Measurements of the total proton–proton cross–section at the ISR", *Physics Letters*, **44B** (1973), 119–124.

Amendolia *et al.* (1973 b)

S.R. Amendolia, G. Bellettini, P.L. Braccini, C. Bradaschia, R. Castaldi, V. Cavasinni, C. Cerri, T. Del Prete, L. Foà, P. Giromini, P. Laurelli, A. Menzione, L. Ristori, G. Sanguinetti, M. Valdata, G. Finocchiaro, P. Grannis, D. Green, R. Mustard, R. Thun, "Total cross–section measurement at the ISR", *Nuovo Cimento*, **174** (1973), 735–755.

Angelis *et al.* (1978)

A.L.S. Angelis, B.J. Blumenfeld, L. Camilleri, T.J. Chapin, R.L. Cool, C. del Papa, L. Di Lella, Z. Dimcovski, R.J. Hollebeek, L.M. Lederman, D. Levinthal, J.T. Linnemann, L. Lyons, N. Phinney, B.G. Pope, S.H. Pordes, A.F. Rothenberg, A.M. Segar, J. Singh–Sidhu, A.M. Smith, M.J. Tannenbaum, R.A. Vidal, J. Wallace–Hadrill, T.O. White, J.M. Yelton, "A measurement of inclusive π^0 production at large p_T from p–p collisions at the CERN ISR", *Physics Letters*, **79B** (1978), 505–510.

Angelis et al. (1979)

A.L.S. Angelis, H.-J. Besch, B.J. Blumenfeld, L. Camilleri, T.J. Chapin, R.L. Cool, C. del Papa, L. Di Lella, Z. Dimcovski, R.J. Hollebeek, L.M. Lederman, D.A. Levinthal, J.T. Linnemann, C. Newman, N. Phinney, B.G. Pope, S.H. Pordes, A.F. Rothenberg, R.W. Rusack, A.M. Segar, J. Singh-Sidhu, A.M. Smith, M.J. Tannenbaum, R.A. Vidal, J.S. Wallace-Hadrill, J.M. Yelton, K.K. Young, "A measurement of the production of massive e^+e^- pairs in proton-proton collisions at $\sqrt{s}=62.4$ GeV", *Physics Letters*, **87B** (1979), 398-402.

Angelis et al. (1980)

A.L.S. Angelis, H.-J. Besch, B.J. Blumenfeld, L. Camilleri, T.J. Chapin, R.L. Cool, C. del Papa, L. Di Lella, Z. Dimcovski, R.J. Hollebeek, L.M. Lederman, D.A. Levinthal, J.T. Linnemann, C. Newman, N. Phinney, B.G. Pope, S.H. Pordes, A.F. Rothenberg, R.W. Rusack, A.M. Segar, J. Singh-Sidhu, A.M. Smith, M.J. Tannenbaum, R.A. Vidal, J.S. Wallace-Hadrill, J.M. Yelton, K.K. Young, "Search for direct single-photon production at large p_T in proton-proton collisions at $\sqrt{s}=62.4$ GeV", *Physics Letters*, **94B** (1980), 106-112.

Aubert et al. (1974)

J.J. Aubert, U. Becker, P.J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T.G. Rhoades, M. Rhode, S.C.C. Ting, S.L. Wu, Y.Y. Lee, "Experimental observation of a heavy particle J", *Physical Review Letters*, **33** (1974), 1404-1406.

Augustin et al. (1974)

J.-E. Augustin, A.M. Boyarsky, M. Breidenbach, F. Bulos, J.T. Dakin, G.J. Feldman, G.E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie, R.R. Larsen, V. Lüth, H.L. Lynch, D. Lyon, C.C. Morehouse, J.M. Paterson, M.L. Perl, B. Richter, P. Rapidis, R.F. Schwitters, W.M. Tanenbaum, F. Vannucci, G.S. Abrams, D. Briggs, W. Chinowsky, C.E. Friedberg, G. Goldhaber, R.J. Hollebeek, J.A. Kadyk, B. Lulu, F. Pierre, G.H. Trilling, J.S. Whitaker, J. Wiss, J.E. Zipse, "Discovery of a narrow resonance in e^+e^- annihilation", *Physical Review Letters*, **33** (1974), 1406-1408.

Banner et al. (1973)

M. Banner, J.L. Hamel, J.P. Pansart, A.V. Stirling, J. Teiger, H. Zacccone, J. Zsembery, G. Bassompierre, M. Croissiaux, J. Gresser, R. Morand, M. Riedinger, M. Schneegans, "Large transverse momentum particle production at 90° in proton-proton collisions at the ISR", *Physics Letters*, **44B** (1973), 537-540.

Berman et al. (1971)

S.M. Berman, J.D. Bjorken, J. Kogut, "Inclusive processes at high transverse momentum", *Physical Review D*, **4** (1971), 3388-3418.

Berman & Jacob (1970)

S.M. Berman, M. Jacob, "Connection between inelastic proton-proton reactions and deep inelastic scattering", *Physical Review Letters*, **25** (1970), 1683-1686.

Bjorken (1969)

J.D. Bjorken, "Asymptotic sum rules at infinite momentum", *Physical Review*, **179** (1969), 1547-1553.

Bjorken & Paschos (1969)

J.D. Bjorken, E.A. Paschos, "Inelastic electron-proton and gamma-proton scattering and the structure of the nucleon", *Physical Review*, **185** (1969), 1975-1982.

Bloom et al. (1969)

E.D. Bloom, D.H. Coward, H. H.DeStaebl, J. Drees, G. Miller, L.W. Mo, R.E. Taylor, M. Breidenbach, J.I. Friedman, G.C. Hartman, H.W. Kendall, "High-energy inelastic $e-p$ scattering at 6° and 10° ", *Physical Review Letters*, **23** (1969), 930-934.

Breidenbach et al. (1969)

M. Breidenbach, J.I. Friedman, H.W. Kendall, E.D. Bloom, D.H. Coward, H. H. DeStaabler, J. Drees, L.W. Mo, R.E. Taylor, "Observed behavior of highly inelastic electron-proton scattering", *Physical Review Letters*, **23** (1969), 935–939.

Bromberg et al. (1977)

C. Bromberg, G. Fox, R. Gomez, J. Pine, S. Stampke, K. Yung, S. Erhan, E. Lorenz, M. Medinnes, J. Rohlf, P. Schlein, V. Ashford, H. Haggerty, R. Inhala, E. Malamud, S. Mori, R. Abrams, R. Delznero, H. Goldberg, S. Margulies, D. McLeod, J. Solomon, R. Stanek, A. Dzierba, W. Kropac, "Observation of the production of jets of particles at high transverse momentum and comparison with inclusive single-particle reactions", *Physical Review Letters*, **38** (1977), 1447–1450.

Bromberg et al. (1978)

C. Bromberg, ..., "Production of jets and single particles at high p_T in 200 GeV hadron-beryllium collisions", *Nuclear Physics*, **B134** (1978), 189–214.

Büsser et al. (1973)

F.W. Büsser, L. Camilleri, L. Di Lella, G. Gladding, A. Placci, B.G. Pope, A.M. Smith, J.K. Yoh, E. Zavattini, B.J. Blumenfeld, L.M. Lederman, R.L. Cool, L. Litt, S.L. Segler, "Observation of π^0 mesons with large transverse momentum in high-energy proton-proton collisions", *Physics Letters*, **46B** (1973), 471–476.

Büsser et al. (1974)

F.W. Büsser, L. Camilleri, L. Di Lella, G. Gladding, A. Placci, B.G. Pope, A.M. Smith, J.K. Yoh, E. Zavattini, B.J. Blumenfeld, L.M. Lederman, R.L. Cool, L. Litt, S.L. Segler, "A search for electron pairs at the CERN ISR", *Physics Letters*, **48B** (1974), 377–379.

Büsser et al. (1975)

"F.W. Büsser, L. Camilleri, L. Di Lella, B.G. Pope, A.M. Smith, B.J. Blumenfeld, S.N. White, A.F. Rothenberg S.L. Segler, M.J. Tannenbaum, M. Banner, J.B. Chèze, J.L. Hamel, H. Kasha, J.P. Pansart, G. Smadja, J. Teiger, H. Zacccone, A. Zylberstejn, "Observation of high mass electron-positron pairs produced in proton-proton collisions at the CERN ISR", *Physics Letters*, **56B** (1975), 482–486.

Cahn & Goldhaber (1989)

R.N. Cahn, G. Goldhaber, *The Experimental Foundations of Particle Physics*, Cambridge: Cambridge University Press, 1989.

Camilleri (1987)

L. Camilleri, "Proton-antiproton physics at the CERN Intersecting Storage Rings", *Physics Reports*, **144** (1987), 51–115.

CESAR (1968)

Cesar Group, *The CERN Electron Storage and Accumulation Ring (CESAR)*, Geneva: CERN 68–8, 6/3/68.

Charpak et al. (1968)

G. Charpak, R. Bouclier, T. Bressani, J. Favier, C. Zupancic, "....", *Nuclear Instruments and Methods*, **62** (1968), 262–xxx.

Christenson et al. (1970)

J.H. Christenson, G.S. Hicks, L.M. Lederman, P.J. Limon, B.G. Pope, E. Zavattini, "Observation of massive muon pairs in hadron collisions", *Physical Review Letters*, **25** (1970), 1523–1526.

Christenson et al. (1973)

J.H. Christenson, G.S. Hicks, L.M. Lederman, P.J. Limon, B.G. Pope, E. Zavattini, "Observation of muon pairs in high-energy hadron collisions", *Physical Review D*, **8** (1973), 2016–2034.

Collins (1971)

P. Collins, "Regge theory and particle physics", *Physics Reports*, **1** (1971), 103–204.

Craigie (1978)

Lepton and photon production in hadron collisions", *Physics Reports*, **47** (1978), 1–108.

Crozon (1987)

M. Crozon, *La Matière Première*, Paris: Éditions du Seuil, 1987.

Darriulat (1980)

P. Darriulat, "Large transverse momentum hadronic processes", *Annual Review of Nuclear and Particle Science*, **30** (1980), 159–210.

Deden et al. (1975)

H. Deden, ..., "Experimental study of structure functions and sum rules in charge-changing interactions of neutrinos and antineutrinos", *Nuclear Physics*, **B85** (1975), 269–288.

Diakonou et al. (1979)

M. Diakonou, C. Kourkouvelis, L.K. Resvanis, T.A. Filippas, E. Fokitis, C. Trakkas, A.M. Cnops, J.H. Cobb, E.C. Fowler, D.W. Hood, S. Iwata, R.B. Palmer, D.C. Rahm, P. Rehak, I. Stumer, C.W. Fabjan, T. Fields, D. Lissauer, I. Mannelli, W. Molzon, P. Mouzourakis, K. Nakamura, A. Nappi, W.J. Willis, "Direct production of high p_T single photons in pp collisions at the CERN ISR", *Physics Letters*, **87B** (1979), 292–296.

Diakonou et al. (1980)

M. Diakonou, C. Kourkouvelis, L.K. Resvanis, T.A. Filippas, E. Fokitis, C. Trakkas, A.M. Cnops, E.C. Fowler, D.W. Hood, R.B. Palmer, D.C. Rahm, P. Rehak, I. Stumer, C.W. Fabjan, T. Fields, D. Lissauer, I. Mannelli, W. Molzon, P. Mouzourakis, W.J. Willis, "A measurement of direct photon production at large p_T at the CERN ISR", *Physics Letters*, **91B** (1980), 296–300.

Di Lella (1984)

L. Di Lella, "ISR Physics" (letter), *New Scientists*, 9 February 1984, 49–50.

Drell & Yan (1970)

S.D. Drell, T.M. Yan, "Massive lepton-pair production in hadron-hadron collisions at high energies", *Physical Review Letters*, **25** (1970), 316–320.

Drell & Yan (1971)

S.D. Drell, T.M. Yan, "Partons and their applications at high energies", *Annals of Physics*, **66** (1971), 578–623.

Eichten et al. (1973)

T. Eichten, H. Faissner, R.J. Hasert, S. Kabe, W. Krenz, J. Von Krogh, J. Morfin, K. Schultze, G.H. Bertrand-Coremans, J. Sacton, W. Van Doninck, P. Vilain, D.C. Cundy, D. Haidt, M. Jaffre, S. Natali, P. Musset, J.B.M. Pattison, D.H. Perkins, A. Pullia, A. Rousset, W. Venus, H. Wachsmuth, V. Brisson, B. Degrange, M. Haguenaue, L. Kluberg, U. Nguyen-Khac P. Petieau, E. Bellotti, S. Bonetti, D. Cavalli, C. Conta, E. Fiorini, C. Franzinetti, M. Rollier, B. Aubert, L.M. Chounet, P. Heusse, L. Jauneau, A.M. Lutz, C. Pascaud, J.P. Vialle, F.W. Bullock, M. Derrick, M.J. Esten, T.W. Jones, J. McKenzie, A.G. Michette, G. Myatt, W.G. Scott, "Measurement of the neutrino-nucleon and antineutrino-nucleon total cross sections", *Physics Letters*, **46B** (1973), 274–280.

Ellis & Kislinger (1974)

S.D. Ellis, M.B. Kislinger, "Implication of parton-model concepts for large-transverse-momentum production of hadrons", *Physical Review D*, **9** (1974), 2027–2051.

Ellis & Stroynowski (1977)

S.D. Ellis, R. Stroynowski, "Large p_T physics: data and the constituent models", *Reviews of Modern Physics* **49** (1977), 753–775.

Fabjan & Ludlam (1982)

C.W. Fabjan, T. Ludlam, "Calorimetry in high-energy physics", *Annual Review of Nuclear and Particle Science*, **32** (1982), 335–389.

Fabjan et al. (1978)

C.W. Fabjan, J. Lindsay, F. Piuz, F. Ranjard, E. Rosso, A. Rudge, S. Serednjakov, W.J. Willis, H.B. Jensen, J.D. Petersen, "A drift chamber vertex detector for intersecting storage rings", *Nuclear Instruments and Methods*, **156** (1978), 267–274.

Faessler (1984)

M. Faessler, "Experiments with alpha particles at the CERN Intersecting Storage Rings", *Physics Reports*, **115** (1984), 1–91.

Feynman (1969)

R.P. Feynman, "Very high energy collisions of hadrons", *Physical Review Letters*, **23** (1969), 1415–1417.

Feynman (1972)

R.P. Feynman, *Photon–Hadron Interactions*, Reading, Ma.: Benjamin, 1972.

Feynman (1974)

R.P. Feynman, "Structure of the proton", *Science*, **183** (1974), 601–610.

Field & Feynman (1977)

R.D. Field, R.P. Feynman, "Quark elastic scattering as a source of high transverse momentum mesons", *Physical Review D*, **15** (1977), 2590–2616.

Fischer (1971)

E. Fischer, *Two kilometres at 10^{-10} torr: the CERN Intersecting Storage Rings for protons*, CERN, ISR–VA/71–55, 10/11/71.

French et al. (1968)

B. French, F. Krienen, T. Hassam, M. Morpurgo, *A proposal for an open magnet system for the ISR experimental region*, CERN, NP internal report 68–5, 11/3/68.

Friedman & Kendall (1972)

J.I. Friedman, H.W. Kendall, "Deep inelastic electron scattering", *Annual Review of Nuclear Science*, **22** (1972), 203–254.

Galison (1983)

P. Galison, "How the first neutral current experiments ended", *Review of Modern Physics*, **55** (1983), 477–509.

Galison (1987)

P. Galison, *How Experiments End*, Chicago: University of Chicago Press, 1987.

Gervaise (1965)

J. Gervaise, "Mesure de distances de haute précision au fil d'invar en micro-géodésie", *Geomètre*, No. 12 (1965), 28–55.

Gervaise (1970a)

J. Gervaise, *Un exemple d'implantation de haute précision: le complexe synchrotron à protons et anneaux de stockage à intersections du CERN*, CERN, ISR–SU/70–1, 26/1/70.

Gervaise (1970b)

J. Gervaise, *Positioning of the Intersecting Storage Rings: The Geodetic Approach*, Geneva: CERN 70–18, 30/6/1970.

Giacomelli (1976)

G. Giacomelli, "Total cross sections and elastic scattering at high energies", *Physics Reports*, **23** (1976), 123–235.

Giacomelli & Jacob (1979)

G. Giacomelli, M. Jacob, "Physics at the CERN-ISR", *Physics Reports*, **55** (1979), 1-132.

Glashow, Iliopoulos & Maiani (1970)

S.L. Glashow, J. Iliopoulos, L. Maiani, "Weak interactions with lepton-hadron symmetry", *Physical Review D*, **2** (1970), 1285-1292.

Hanson et al. (1975)

G. Hanson, G.S. Abrams, A.M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G.J. Feldman, C.E. Friedberg, D. Fryberger, G. Goldhaber, D.L. Hartill, B. Jean-Marie, J.A. Kadyk, R.R. Larsen, A.M. Litke, D. Lüke, B.A. Lulu, V. Lüth, H.L. Lynch, C.C. Morehouse, J.M. Paterson, M.L. Perl, F.M. Pierre, T.P. Pun, P.A. Rapidis, B. Richter, B. Sadoulet, R.F. Schwitters, W. Tanenbaum, G.H. Trilling, F. Vannucci, J.S. Whitaker, F.C. Winkelmann, J. Wiss, "Evidence for jet structure in hadron production by e^+e^- annihilation", *Physical Review Letters*, **35** (1975), 1609-1612.

Harari (1978)

H. Harari, "Quarks and leptons", *Physics Reports*, **42** (1978), 235-309.

Herb et al. (1977)

S.W. Herb, D.C. Hom, L.M. Lederman, J.C. Sens, H.D. Snyder, J.K. Yoh, J.A. Appel, B.C. Brown, C.N. Brown, W.R. Innes, K. Ueno, T. Yamanouchi, A.S. Ito, H. Jöstlein, D.M. Kaplan, R.D. Kephart, "Observation of a dimuon resonance at 9.5 GeV in 400-GeV proton-nucleus collisions", *Physical Review Letters*, **39** (1977), 252-255.

Hermann et al. (1987)

H. Hermann, J. Krige, U. Mersits, D. Pestre, *History of CERN*, vol. 1, Amsterdam: North Holland 1987.

Hermann et al. (1990)

H. Hermann, J. Krige, U. Mersits, D. Pestre, *History of CERN*, vol. 2, Amsterdam: North Holland 1990.

Hine (1964)

M.G.N. Hine, *A short description of the project for Intersecting Storage Rings at CERN and their place in European physics*, CERN, DIR/AP/143, 30/11/64.

Horn (1972)

D. Horn, "Many-particle production", *Physics Reports*, **4** (1972), 1-65.

Hübner (1977)

K. Hübner, *ISR Performance for Pedestrians*, Geneva: CERN 77-15, 1977.

Hyams & O'Neil (1968)

B. Hyams, G.K. O'Neil, *A momentum analysis system for ISR reactions*, CERN, NP internal report 68-30, 11/9/68.

ISR (1964)

CERN Study Group on New Accelerators, *The design study of Intersecting Storage Rings (ISR) for the Cern Proton Synchrotron*, CERN, AR/Int. SG/64-9, 12/5/64, re-numbered as CERN/542.

ISR (1969)

Intersecting Storage Rings, CERN, Technical Notebook No. 5, May 1969;

ISR (1974)

Intersecting Storage Rings, Technical Notebook No. 5, CERN/PIO 74-2, January 1974.

Jacob (1984)

M. Jacob, "The role of the ISR in the development of particle physics", in Jacob & Johnsen (1984), 21-81.

Jacob & Johnsen (1984)

M. Jacob, K. Johnsen, *A review of accelerator and particle physics at the CERN Intersecting Storage Rings*, Geneva: CERN 84-13, 30/11/84.

Jacob & Ladshoff (1978)

M. Jacob, P.V. Landshoff, "Large transverse momentum and jet studies", *Physics Reports*, **48** (1978), 285-350.

Johnsen (1965)

K. Johnsen, "The CERN Intersecting Storage Rings Project", *5th International Conference on High Energy Accelerators, Proceedings* (Frascati 1965), Roma: CNEN, 1966; pre-print in ISR Archive, CERN.

Johnsen (1967)

K. Johnsen, "The CERN Intersecting Storage Rings Project", *6th International Conference on High Energy Accelerators, Proceedings* (Cambridge 1967), Cambridge, 1967, 58-63.

Johnsen (1973)

K. Johnsen, "The CERN Intersecting Storage Rings", *Nuclear Instruments and Methods*, **108** (1973), 205-223.

Johnsen (1984)

K. Johnsen, "The ISR and accelerator physics", in Jacob & Johnsen (1984), 1-19. A substantially identical version of this paper is Johnsen (1986).

Johnsen (1986)

K. Johnsen, "The ISR and accelerator physics", in *Particle Accelerators*, **18** (1986), 167-182. This is a revised version of Johnsen (1984).

Johnsen & Van Hove (1966)

K. Johnsen, L. Van Hove, *Status report on ISR*, CERN/SPC/226, 12/5/66.

Johnsen et al. (1965)

K. Johnsen, E. Keil, B. de Raad, L. Resegotti, *Alternatives to the presently proposed ISR structure*, CERN, AR/Int. SG/65-21, 29/11/65.

Keil (1972)

E. Keil, *Intersecting Storage Rings*, Geneva: CERN 72-14, 21/7/72.

Kogut & Susskind (1973)

J. Kogut, L. Susskind, "The parton picture of elementary particles", *Physics Reports*, **8** (1973), 75-172.

Krige (1987)

J. Krige, "Case studies of some important decisions", chapter 8 in Hermann *et al.* (1987), p. 237-292.

Krige (1990)

J. Krige, "Finance policy: the debates in the Finance Committee and the Council over the level of the CERN budget", Chapter 10 in Hermann *et al.* (1990), 571-635.

Kuhn (1970)

T.S. Kuhn, *The Structure of Scientific Revolutions*, 2nd ed., Chicago: Chicago University Press, 1970

Kuti & Weisskopf (1971)

J. Kuti, V. Weisskopf, "Inelastic lepton-nucleon scattering and lepton pair production in the relativistic quark-parton model", *Physical Review D*, **4** (1971), 3418-3439.

Lederman (1976)

L. Lederman, "Lepton production in hadron collisions", *Physics Reports*, **26** (1976), 149-181.

Lederman (1978)

L. Lederman, "The upsilon particle", *Scientific American*, **239**:4 (1978), 60–68.

Marciano & Pagels (1978)

W. Marciano, H. Pagels, "Quantum chromodynamics", *Physics Reports*, **36** (1978), 137–276.

Minten (1969)

A. Minten, "Plans for physics with the Intersecting Storage Rings", in *Proceedings of the 1969 CERN School of Physics*, Leysin, Geneva: CERN 69–29, 19/11/69, 97–122.

Musset & Vialle (1978)

P. Musset, J.P. Vialle, "Neutrino physics with gargamelle", *Physics Reports*, **39** (1978), 1–130.

Pestre (1990 b)

D. Pestre, "The second generation of accelerators for CERN, 1956–1965: the decision-making process", in Herman *et al.* (1990), 679–780.

Pestre (1990 a)

D. Pestre, "The organization of the experimental work around the Proton Synchrotron, 1960–1965: the learning phase", in Hermann *et al.* (1990), 429–502.

Pickering (1984)

A. Pickering, *Constructing Quarks*, Edinburgh: Edinburgh University Press, 1984.

Resegotti (1969)

L. Resegotti, *Progress report on the Split-Field Magnet for the ISR*, CERN, ISR–MAG/69–58, September 1969.

Richter (1977)

B. Richter, "From the psi to charm: the experiments of 1975 and 1976", Nobel Lecture, *Reviews of Modern Physics*, **49** (1977), 251–266.

Ruggiero (1968)

A.G. Ruggiero, *Beam stacking with suppressed buckets in the ISR*, Geneva: CERN 68–22, 4/6/68.

Samuel (1970)

R.L. Samuel, "La grande enceinte à ultra-vide des I.S.R. du CERN", *Industries Atomiques*, No. 7/8, 1970, 3–13.

Schnell (1966)

W. Schnell, *Stacking with missing buckets, another way of gaining the ISR/CPS circumference factor*, CERN, ISR–RF/66–34, 10/11/66.

Schnell (1967)

W. Schnell, "Stacking in proton storage rings with missing buckets", *6th International Conference on High Energy Accelerators, Proceedings* (Cambridge 1967), Cambridge, 1967, 85–89.

Schnell (1972)

W. Schnell, *About the feasibility of stochastic dumping in the ISR*, CERN, ISR–RF/72–46, November 1972.

Schwitters & Strauch (1976)

R.F. Schwitters, K. Strauch, "The physics of e^+e^- collisions", *Annual Review of Nuclear Science*, **26** (1976), 89–149.

Sivers *et al.* (1976)

D. Sivers, R. Blankenbecler, S. Brodsky, "Large transverse momentum processes", *Physics Reports*, **23** (1976), 1–121.

Steinberger (1968)

J. Steinberger, "...", in CERN, NP internal report 68–34 (1968).

Stroynowski (1981)

R. Stroynowski, "Lepton pair production in hadron collisions", *Physics Reports*, **71** (1981), 1–50.

Taubes (1989)

G. Taubes, *Nobel Dreams. Power, Deceit, and the Ultimate Experiment*, New York: Random House, 1989.

Ting (1977)

S.C.C. Ting, "The discovery of the J particle: a personal recollection", Nobel Lecture, *Reviews of Modern Physics*, **49** (1977), 235–249.

Van der Meer (1972)

S. Van der Meer, *Stochastic damping of betatron oscillations in the ISR*, CERN, ISR-PO/72-31, August 1972.

Watkins (1986)

P. Watkins, *Story of the W and Z*, Cambridge: Cambridge University Press, 1986.

Wilczek (1982)

F. Wilczek, "Quantum chromodynamics: the modern theory of strong interactions", *Annual Review of Nuclear and Particle Science*, **32** (1982), 177–209.

Winter (1969)

K. Winter, *A summary of discussions on a large analysis system of ISR reactions*, CERN, NP Internal Report, 69-2, 14/2/69.

Yan (1976)

T.M. Yan, "The parton model", *Annual Review of Nuclear Science*, **26** (1976), 199–238.

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This report is intended for inclusion, in modified form, in Volume III of the History of CERN. Volume I was published in 1987, and covered the launching of the European Organization for Nuclear Research. Volume II, concerned with building the laboratory and running it until 1965, was published in 1990. They are available from

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