Message from the President of Council

A year ago, I was nominated to preside over Council and left the smooth routine of the Swiss delegation. This first year of the millennium was an "annus horribilis" for many countries, including Switzerland, which endured a series of disasters on a national scale. At CERN too, the issues raised in 2001 were very difficult ones, even if not life-threatening. But CERN’s history shows us our institution has dealt previously with difficult times.

In the aftermath of World War II, during the European Conference for Culture in Lausanne in December 1949, the problem of co-operation in nuclear matter research was raised for the first time. A member of the Workers’ Party raised a question in the Geneva Cantonal Parliament, expressing concern about installing a laboratory in Geneva, and remarked: "It seems strange in the present circumstances that the Geneva Government should, merrily and without hesitation, be agreeing to the idea of Geneva becoming the centre of an ‘atomic’ institute. Which could mean that, one day, we shall be a target for atomic bombs". In November 1952 the Workers’ Party announced that it had launched a local referendum seeking to prohibit the establishment of a nuclear physics institute in the canton of Geneva. Some members of the local community had expressed surprise that Switzerland should be called upon to play a role in the development of such an institution. But the people of Geneva massively rejected the prohibition motion, and the Laboratory was born.

50 years later, CERN was to be faced with another disagreeable surprise, this time arising from the LHC project: planned resources are not sufficient to complete the project.

But 2001 also had its highlights: a significant number of scientific achievements punctuating the first year of the millennium:

- After 10 years of detector development, data collection and analysis, the NA48 experiment collaboration announced its final result on direct charge-parity (CP) violation. This subtle effect explains Nature’s preference for matter over anti-matter (see page 29).
- In June 2001, CERN received a century Achievement Award from the Computerworld Honors Program for its innovative application of information technology for the benefit of society (see page 28).
- Director-General Luciano Maiani said "this is an important recognition of CERN’s excellence in information technology, a reward for the teams of physicists from LEP experiments who contributed to the development and implementation of this new architecture".
- CERN announced the creation of the CERN openlab for DataGrid applications. Three leading information technology firms have joined CERN to push forward this groundbreaking project in advanced distributed computing (see page 26).
- In September 2001, CERN hosted in Geneva the 17th Magnet Technology Conference, the world’s largest, focusing on magnets and their applications (see page 37).
- CERN Council approved the creation of an External Review Committee to help to resolve the unpleasant surprise of 2001.

To conclude, I quote from a letter from Dr Robert A. Eisenstein of the US National Science Foundation, a member of the US observer team at CERN Council: "CERN is widely viewed also in other countries as the most successful example of how large-scale, truly world-wide international collaborations can be realized with great efficiency, the only example now in existence of such large international scientific collaborations".

I am convinced that CERN has the institutional strength, backed by its competent staff, to transform an “horribilis” event into a “mirabilis” one.
As the year began, the question on everyone’s lips was whether the decision to switch off the Large Electron Positron collider (LEP) had been the right one. Towards the end of 2000, LEP scientists had reported possible signs of the mysterious and long-awaited Higgs particle. With LEP scheduled to be decommissioned to make way for the LHC, my directorate and I were faced with the difficult choice of either closing LEP as planned, leaving the Higgs question unresolved, or running the collider for another year. Doing so would have led to considerable extra cost and would undoubtedly have delayed the LHC. We took the painful decision to close LEP and push ahead with the LHC.

After careful scrutiny of the LEP data in 2001, hints of a Higgs particle were still there, albeit not as significantly as initially thought. It was clear that a further year of running would have not been conclusive, and that the hunt for the Higgs should continue at Fermilab’s Tevatron and ultimately at the LHC. Our decision to close LEP in 2000 had been the right one.

In the second half of the year, CERN experienced a bitter blow. An in-depth examination of the cost-to-completion of the LHC pointed to a significant cost overrun. This examination considered all aspects of the project, from accelerator hardware to installation. Launched in spring 2001, it followed a similar analysis carried out in 2000 for the LHC’s detectors and computing infrastructure. By the end of August, we were able to include the results of a call for tender for the largest, and most technologically challenging, item on the LHC bill - the assembly of over 1200 superconducting dipole magnets that will equip the ring. That gave us the full picture.

A combination of past funding shortfalls for items such as magnet prototyping and cryogenics, unforeseeable obstacles encountered in civil engineering, computing, manpower for installation, and an unexpectedly large cost for the dipole magnets added up to a total some 30% higher than foreseen in 1996. The extra cost of the magnets has since been somewhat attenuated through careful negotiation with the supplying firms.

In a project of this magnitude, some cost increase is almost inevitable, but the size of the final figure took us by surprise. Immediate action was called for. Internal Task Forces were set up to scrutinize the cost and scientific merit of our scientific programmes, to find areas for savings in-house, to examine CERN-wide restructuring, and to identify improved tools for managing CERN resources. In November, Council established an External Review Committee to take a fresh look at the LHC and at CERN in general. Chaired by Robert Aymar, Director of the international thermonuclear experimental reactor, ITER, this committee will report to Council in June 2002.

Throughout the year, CERN continued to do world-class research. The first results from the Antiproton Decelerator included new precision measurements of vital antiproton parameters. Superb measurements of the tiny imbalance between matter and antimatter by the NA48 experiment put the phenomenon beyond doubt. And civil engineering for the CERN neutrinos to Gran Sasso project pushed ahead vigorously to remain on track to become an important new player on the international research scene from 2005.

To conclude, I would like to return to the LHC, CERN’s major project for the next two decades. Technologically the LHC is on course. To restore its financial well-being, remedial medium- and long-term solutions are being prepared. The medicine may be unpleasant, but it will ensure the LHC’s health and assure the future of CERN and of particle physics globally. As always, CERN’s successes are its people’s successes. Ever mindful of this, the laboratory introduced a new career structure and advancement scheme in 2001. Its aim is to ensure recognition of achievement within the Organization and to reward merit. Our new career structure reinforces staff-management relations at a vital time and puts us in good stead to face the future.
What concerns CERN?

A world laboratory for studying the Universe

CERN, the European Organization for Nuclear Research, is one of the world’s largest and most respected international centres for scientific research. Its business is fundamental physics — finding out what the Universe is made of and how it works. At CERN, the world’s largest and most complex scientific machines are used to study Nature’s ultimate building blocks — the fundamental particles. By studying what happens when these minute fragments of matter collide, physicists unravel the basic laws of Nature.

When CERN was founded in 1954, it was one of Europe’s first joint ventures, with specialists working together to build scientific research installations that were beyond the means of individual nations. It has gone on to become a shining example of international collaboration, a laboratory for the world. From the original 12 signatories of the convention establishing CERN, membership has grown to 20 European Member States, and nations from all over the globe contribute to and participate in the research programme.

CERN’s machines are particle accelerators and detectors, and CERN’s users are physicists. The Laboratory’s oldest still-functioning accelerator is the Proton Synchrotron (PS); commissioned in 1959, for a brief period it supplied the world’s highest particle energies. The Super Proton Synchrotron (SPS), fed by the PS, was commissioned in 1976, when it was the world’s largest particle accelerator. In the early 1980s it was the scene of research which brought CERN its first Nobel Prize (1984). The LEP electron–positron collider, built in a 27-kilometre underground tunnel and fed by the PS and the SPS, was the Laboratory’s flagship research machine from 1989 to 2000.

CERN’s successive generations of machines attain higher energies, each machine feeding the next. The LEP ring has now been dismantled. In its tunnel CERN is building the Large Hadron Collider (LHC), also fed by the PS and the SPS, to enable the world’s particle physicists to probe even deeper into the heart of matter.

While CERN provides these giant machines, physicists build the giant detectors which record what happens when the particles collide or interact. The detectors are operated by teams of physicists in universities and national research centres. As physics has advanced, experiments have become progressively larger, and a major collaboration can now include more than a thousand scientists. Altogether, the CERN research programme involves over 6000 researchers from some 500 research centres and universities throughout the world.

This research pushes technology to its limits, bringing important benefits to society. Particle accelerators (much smaller than those used at CERN) are employed widely in industry and medicine. Techniques developed for particle detectors have been successfully adapted for medical imaging and for security scanning. The most well-known of CERN’s spin-offs is the World Wide Web, invented in 1989 in response to the need for new global communications. For the future, new physics data handling requirements are influencing developments in computer networking.
The coldest locality in the Universe

CERN and the LHC

CERN is building the Large Hadron Collider (LHC), a technologically challenging 27-kilometre ring of superconducting magnets, to enable physicists to study proton–proton and other types of collision at unprecedented energies. Scheduled to begin operation in 2007, the LHC will open up new physics horizons, probing interactions between the quark and gluon constituents of protons in an energy range where new behaviour is expected to reveal key insights into the underlying mechanisms of Nature. High on this list is the Higgs effect, ultimately responsible for the different masses of the various elementary particles which make up matter.

The LHC’s high-energy beams, circulating in separate vacuum chambers, will be brought into collision at four places around the ring. Gigantic detectors are being constructed around these beam intersections to monitor and record the results of the collisions.

As well as reaching unprecedented collision energies, the LHC will also attain collision rates never before achieved for protons. In this way, the experiments will collect larger data samples in the search for extremely rare processes.

The recording and analysis of all this data will require enormous amounts of computing power. Because the collaborations building and operating the LHC detectors involve physicists from research centres all over the world, this data and computing power must be instantly accessible around the globe. The LHC will open a new era in data communications as well as physics and cryogenics.

Heat is the result of atomic and molecular motion. However, at a temperature of -273.15 °C, all atoms reach their lowest possible energy state, and there is no more heat. Physicists therefore call this temperature ‘absolute zero’. The 2001 Nobel Prize for Physics was awarded to three researchers who had investigated what happens to atoms when they are cooled to within a tiny fraction of a degree of absolute zero, a phenomenon called ‘Bose–Einstein condensation’. However these and other experiments were conducted with very tiny test samples.

[Low-temperature physics employs the ‘kelvin’ (K) scale, named after the Scottish physicist Lord Kelvin (William Thomson, 1824–1907). The zero of this scale is absolute zero, and the temperature units are the same as those of the centigrade scale. Thus 0 °C is +273.15 K.]

Outer space is mainly empty and very cold. Away from the clusters of galaxies where matter is concentrated, outer space contains little else than the faint cosmic background radiation, the distant rumble of the Big Bang that created the Universe some 12 thousand million years ago. This background radiation has now cooled to a frigid 2.735 K – colder than the temperature (4.2 K) needed to condense helium, the gas most difficult to liquefy.

How the Large Hadron Collider (LHC) will look in CERN’s 27-kilometre tunnel. The LHC, cooled by superfluid helium at -271 °C, will be colder than the depths of outer space.
NASA’s cosmic background explorer satellite (COBE) launched in 1989 made the first measurements of the cosmic background radiation, the faint echo of the Big Bang that created the Universe. It also pioneered the use of superfluid helium for physics experiments in space. After COBE had scanned the sky for 306 days, its superfluid helium finally evaporated.

Superbehaviour

Helium was first liquefied in 1908 by Heike Kamerlingh Onnes (Nobel Physics Prize, 1913). This achievement opened up new areas of physics study. However, for 15 years the only place in the world where liquid helium existed was Onnes’ laboratory in Leiden. Materials cooled to within a few degrees of absolute zero showed bizarre behaviour, as did liquid helium itself. However, it took time for the real nature of these effects – what are now known as superconductivity and superfluidity – to become clear.

Superconductivity is the virtual disappearance of electrical resistance at liquid helium temperatures, and superfluidity, which sets in at 2.17 K, is the virtual disappearance of viscosity. Superfluid helium flows without resistance, as if no internal friction acts in the liquid, and can flow through microscopic holes. If the vessel containing superfluid helium is rotated, the helium inside stays still, and can even detect the rotation of the Earth. If a small cup of superfluid helium is placed in a larger one, with the liquid levels initially different, the two levels quickly equalize — in fact both containers are covered by a microscopic film of superfluid helium which makes the liquid flow from one container to another.

In the latter half of the 20th century, new technology opened up the study of liquid helium. Its behaviour, initially a mystery, also became better understood. Helium becomes superfluid because of the quantum phenomenon of Bose–Einstein condensation. The atoms of superfluid helium have a collective behaviour. Sixty years after its discovery, superfluid helium remains an advanced research topic in condensed-matter physics, an archetypal ‘quantum fluid’, and the LHC will be the largest sample of quantum fluid ever assembled.

The famous ‘fountain effect’ in superfluid helium is the result of its very low viscosity. Only the superfluid component of helium can pass through a tiny ‘superleak’. Shining a light on the helium heats it up and locally spoils its superfluidity, thus creating a current of fresh superfluid which squirts upwards.
One hundred years ago, Max Planck discovered that the spectrum of light emitted by a hot object could be explained only if the radiators had discrete energy states, rather than a continuous range. This led some physicists to suspect that electromagnetic radiation such as light and heat was packaged, or ‘quantized’, rather than being a continuous stream. By 1905, Albert Einstein concluded that the radiation itself was emitted as bursts (‘quanta’) of energy.

It was not until 1924 that the Indian physicist Satyendra Nath Bose suggested to Einstein how Planck’s theory could be derived from first principles. Duly impressed by this, Einstein began work himself on the quantum theory of radiation. Thus was born the concept of Bose–Einstein statistics for quanta (‘bosons’) carrying an integer value of angular momentum (spin). There is no limit on the number of bosons that can simultaneously occupy any one quantum state.

Einstein realized that bosons should undergo a change of behaviour at very low temperatures, accumulating (condensing) in the lowest possible energy state – the phenomenon of Bose–Einstein condensation.

In 1938, Fritz London suggested that this mechanism ultimately could contribute to the special behaviour of superfluid helium. The suggestion turned out to be correct, but the behaviour of liquid helium is not the ideal case of Bose–Einstein condensation.

In 1995, physicists observed pure Bose–Einstein condensation in a dilute gas of non-interacting atoms. For this achievement, Eric Cornell and Carl Wieman of the Massachusetts Institute of Technology were awarded the 2001 Nobel Physics Prize.

Superconductivity is essential for the LHC, which will be the largest superconducting installation in the world. In addition, it will contain the largest amount of superfluid helium – some 60 tonnes – ever assembled. Harnessing superfluidity on this scale calls for some very special technology, providing efficient production and long-distance transport of high refrigeration capacity at very low temperatures.

In a collaboration between CERN and the German physics research centre in Karlsruhe, the application of superfluid helium was pioneered in the early 1970s for use in superconducting radiofrequency separators to supply enriched levels of certain types of particle.

In the early 1970s, a CERN–Karlsruhe collaboration pioneered the large-scale use of superfluid helium with this radiofrequency particle separator. Until then, superfluid helium had been a laboratory curiosity.

The large-scale use of superfluid helium was further opened up in the 1980s for the large magnets needed to contain the high-temperature gases in controlled thermonuclear fusion experiments. High performance radiofrequency systems, such as those used to power the Colliding Electron Beam Accelerator Facility (CEBAF) at the Jefferson Laboratory, Newport News, USA, use superfluid helium cooling. Superfluid helium is also used to minimize background ‘noise’ in highly sensitive electronic detectors mounted in research satellites.

The French Tore Supra controlled thermonuclear fusion experiment was the first major physics installation to use superfluid helium as a coolant.
The LHC will be the largest cryogenic system in the world. Why does such a particle accelerator need low temperatures?

The LHC has to use powerful electromagnets to keep its high-energy particles on a circular track. To provide the strong fields needed to grip its high-energy particles, the LHC electromagnets exploit the phenomenon of superconductivity, in which an electric current passes almost without resistance. In this way, the LHC magnets can be powered to very high fields and at minimal cost. Most materials which become superconducting only do so at liquid helium temperatures. As well as being vitally dependent on temperature, superconductivity also depends on other factors. If the current is increased beyond a critical level, the material ceases to be superconducting. This critical current itself depends on temperature as well as on the applied magnetic field. To maintain the required high currents and avoid such problems, the liquid helium bathing the LHC's electromagnets will be cooled down to just 1.9 K, at which temperature helium is a superfluid.

Providing cryogenics on this scale calls for some very special technology, providing efficient refrigeration capacity and long-distance transport of this capacity at very low temperatures. The LHC represents a major fraction of the world cryogenic effort, not only in sheer volume but also for research and development work. Most of the world's major cryogenic suppliers are involved in the LHC effort, providing enormous amounts of high-quality materials.

Cooling the LHC ring

To maintain its 27-kilometre ring at superfluid helium temperatures, the LHC's cryogenic system will have to supply an unprecedented total refrigeration capacity of some 150 kW at 4.5 K and 20 kW at 1.9 K distributed around the ring. The LHC cryogenic system has been the subject of an extensive industrial development programme between CERN and the French Commissariat d'Energie Atomique (CEA). This programme benefited from experience gained in construction of the CEA's Tore Supra experimental thermonuclear fusion facility in the 1980s.
About half of the refrigeration capacity used at the LHC was originally installed for LEP – CERN’s electron–positron collider. There its job was to provide the liquid helium supply for the superconducting radiofrequency cavities which boosted the energy of the particle beams. For the LHC, this cryogenic supply had to be doubled in size to provide much more liquid helium, and extended to cool helium from 4.5 K down to 1.9 K using several stages of centrifugal compressors.

As well as being highly efficient, the compressors must not contaminate the helium in any way. After significant development work in industry, the LHC will use centrifugal compressors which operate like spin-driers, hurling helium outwards into the compressor outlets. These operate at extremely high speeds (up to 900 revolutions per second) requiring special active magnetic bearings.

For the cooling system needed to maintain the LHC ring at 1.9 K, development work focused on specially-designed low-pressure heat exchangers, volume and hydrodynamic compressors, and optimal thermodynamic cycles. Special large-scale experiments were carried out to measure the flow pattern of superfluid helium over long distances.

Cryogenics for the eight sectors of the machine will be supplied by eight powerful refrigerator units distributed around the ring. The superconducting magnets are bathed in static superfluid helium under pressure. This high pressure keeps air out and minimizes electrical problems due to bubbles of vapour. Superfluid helium at 1.9 K has a very high thermal conductivity and is able to conduct away heat a thousand times better than a metallic conductor like copper. With almost no viscosity, superfluid helium penetrates tiny cracks, 'soaking' deep inside the magnet coils to absorb any deposited or generated heat. This heat is quickly transported to a heat exchanger pipe containing a mixture of saturated vapour and superfluid helium arranged in a series of 107-metre cooling loops all around the ring. The low-pressure vapour is returned to a header, where low-pressure compressors take it to atmospheric pressure (at 1.9 K, saturated superfluid helium is at a pressure of 1.6 kilopascal, 1.6% of atmospheric pressure).

The LHC uses eight 18-kW cryoplants, four of them new and four upgraded from the cryogenics used for LEP. This photo shows one of the new 18-kW 4.5-K refrigerator units. To reduce the cooling required at 1.9 K, heat is removed as far as possible at higher temperatures. The magnet supports, for example, have intermediate heat intercepts to reduce heat entering the magnet cold-masses. Electrical connections, instrumentation and the feet on which the magnets stand are the only points where heat transfer can happen through conduction. They are all carefully designed to draw off heat progressively. The feet are made of 4-mm-thick glass-fibre composite material with layers of aluminium and steel heat intercepts. Each foot supports 10,000 kg of magnet.

Making the current leads themselves superconducting minimizes the heat entering the cold system. Instead of classic materials like copper which are good thermal conductors, these current leads use newly discovered materials which become superconducting at around 80 K and which have a lower thermal conductivity.

Cold compressor cartridges ready for installation. Four stages in series will compress superfluid helium from 1.6 to 60 kilopascal.
The metallic conductors carrying the current in the LHC's superconducting electromagnets are a key element in the manufacturing process. The niobium–titanium alloy used in the LHC represents a major fraction of the total world production of superconducting raw material – 28% over a five-year period. In addition to the sheer volume of the production process, the finished product has to be of extremely high quality.

The magnet coils for the LHC are wound from 'Rutherford' cable, so called after the UK laboratory where it was developed. This cable consists of up to 36 twisted 15-mm strands, each strand being made up in turn of up to 8800 individual filaments, each filament having a diameter as small as 7 micrometres.

The 27-kilometre circumference of the LHC calls for 7000 km of cable, corresponding to about 240,000 km of strand – enough to circle the Earth six times at the Equator. If all the component filaments were unravelled, they would stretch from the Earth to the Sun!

The raw material for this conductor is 470 tonnes of niobium–titanium alloy and 26 tonnes of niobium sheet supplied by Wah-Chang in the USA. To make the filaments, a 110–kg billet of niobium–titanium 195 mm long and 850 mm across, protected by a niobium sheet and enclosed in a copper canister, is forced through a nozzle under pressure and then drawn out into hexagonal wires about 2 mm across. In the next stage of the process, 8800 of these hexagons are packed together in another copper can, for extrusion and drawing to the required strand size, ready for cable manufacture.

The cables are provided by specialist suppliers – four in Europe, one in the USA and one in Japan. The provision of the superconducting material to the European suppliers is covered by the USA’s contribution to the LHC.

Quality control for this cable is extremely important. A few broken filaments deep inside the conductor matrix are not a problem, however large breaks would quickly ruin magnet performance. CERN therefore strictly controls all stages in the manufacture of the cable. All billets of niobium–titanium must be certified as conforming to a strict specification. Then the cabling run is checked to ensure that all strands come from previously approved billets. During the cabling run, samples are continually monitored before an approval for shipment is issued. The whole cable is then stringently checked before being made available for magnet manufacture. To handle all these complicated tests, a large array of testing equipment has been developed and built at CERN. Some tests are also carried out at Brookhaven in the USA.

During 2001, about half the raw niobium–titanium was processed, but it became clear that cable production was already running behind the schedule originally foreseen. This was mainly because of the difficulties of maintaining the required cable quality under mass production conditions. Certain supplier responsibilities were reassigned, and with cable supply being critical to the success of the whole project, such flexibility could still continue to play an important role.
Although the LHC pre-series magnets do not yet conform to the final specification as far as the field quality is concerned, they will nevertheless be installed in the tunnel and form part of the machine. Nine pre-series dipoles became available during the year (compared with one in 2000). A further seven dipoles were near to completion in industry, together with coils for 15 more. The final assembly (yoke, shrinking cylinder, and end terminations) of these magnets was done at CERN from collared coils supplied by industry.

Both at CERN and with the suppliers, the switch from tooling used to build prototypes to the series production tooling was difficult. This included the development of special robot-assisted welding and a laser-controlled system for precision monitoring and control of dipole geometry. Systematic measurements in industrially manufactured magnets had revealed the need for such a system.

The last pre-series dipole magnet welded at CERN left the laboratory on 18 December for completion in industry. To complete the LHC dipole inventory, all the remaining 1200 or so dipoles will be manufactured in industry.

**Going into the cold**

LHC technical systems reached an important milestone in 2001 with the successful commissioning of String 2, a chain of prototype magnets complete with all necessary powering, control, and protection systems. The final test-bed for validating LHC systems, String 2 is the last chance to confirm design choices before installation of the new accelerator underground.

The initial String 2 configuration consisted of three prototype dipole magnets, two quadrupoles, and a full-scale prototype cryogenic distribution line, including the high-temperature superconductor 13-kA current leads. Three more dipoles are scheduled to be added, turning String 2 into a full cell of the LHC accelerator. Fifteen electrical powering circuits with final-design power converters, and a digital current regulation system capable of measuring magnet currents to a few parts per million complete the String 2 setup.

String 2 was cooled down to 1.9 K in mid-September for systems validation tests to begin. With so much energy stored in superconducting magnets, a vital part of any major cryogenic installation is the 'quench protection', to protect...
the installation should the magnets suddenly cease to become superconducting. Testing the systems that detect quenches and protect the magnets was therefore the first part of the String 2 validation programme and was carried out before the magnet currents were increased to their nominal level of 11,850 amps (8.3 T). Continuing validation tests cover normal running conditions and provoked quenches.

The ‘Crab’, specially designed at CERN and manufactured in Finland, transports LHC superconducting magnets and components in the assembly and test area.

Arrival at CERN of the first batch of over 1200 vacuum vessels which will house the LHC superconducting dipoles.

Over the past two years, some 360 6-metre dipoles and 180 4-metre quadrupoles have arrived at CERN after making the 6000-kilometre journey from the Budker Institute, Novosibirsk. Seated on the magnets are, left–right, LHC Project Director Lyn Evans, Director-General Luciano Maiani, Budker Institute Director Alexander Skrinsky and CERN Accelerator Director Kurt Hübner.
Two of the major civil engineering packages for the LHC naturally focus on the vast infrastructure to house the ATLAS and CMS detectors. Point 1, the nearest point of the LHC tunnel to the main CERN site, will be the home of the mighty ATLAS detector, while Point 5, further round the ring, will house CMS.

At Point 1, all but two of the new surface buildings were completed in 2001. Underground, the three new access shafts are complete, as is the US15 service cavern. The underground work is dominated by the huge UX15 cavern where the ATLAS experiment will eventually be installed. During the year, the 11,000-tonne roof vault was suspended using 32 slender tensioned steel cables, and excavation reached the level of the existing ring tunnel.

At Point 5, the ground had to be frozen before underground excavation could begin in earnest in 1998. Despite this having taken longer than foreseen, good progress is being made, with two major shafts completed during the year. A major achievement was the 30-m-high ‘pillar’ support between the two main caverns. During the year, this was fully excavated and concreted. With the support in place, excavation work began on the two main underground caverns on either side of the pillar.

Although the LHC inherits the 27-kilometre tunnel that was built for LEP in the 1980s, the LHC’s physics experiments are on a much larger scale. Vast new underground caverns, access shafts, surface buildings and service galleries have to be constructed. In 2001, the enormity of these new underground installations could begin to be appreciated.

During 2001, excavations for the UX15 cavern which will eventually house the ATLAS detector reached the level of the existing ring tunnel. When complete, the excavation will be 40 m high and 35 m wide – large enough in principle to accommodate the Arc de Triomphe.

Civil engineering progress at Point 6, showing the junction of the main LHC ring with the ‘beam dump’ tunnel into which the stored LHC beams will be shunted when no longer required.
A major achievement in 2001 was the ‘pillar’ support between the two main caverns at Point 5. Only the top of the pillar is visible here.

Other civil engineering packages focus on the work to adapt the existing tunnel for the LHC machine and to excavate the transfer tunnels to connect with the existing CERN accelerators.

Layout of the LHC ring, showing the two tunnels (in red) that will transfer particles from the SPS synchrotron into the LHC. The boring of these tunnels was completed in 2001.

Breakthrough! On 15 May, the first of the transfer tunnels to supply LHC protons linked with the tunnel in which the LHC will be installed. Left, Director-General Luciano Maiani; right, LHC Project Director Lyn Evans. The link for the second tunnel was made later in the year.

LEP dismantling

CERN’s 27-kilometre tunnel was built in the 1980s to house the LEP electron–positron collider, which began operation in 1989. LEP was finally closed in November 2000. In 2001, work began to dismantle 30,000 tonnes of LEP equipment in order to clear the tunnel for the LHC. By the end of the year almost all LEP equipment had been removed, so that surveying could begin prior to positioning LHC equipment.

CERN has signed an agreement with the French authorities classifying LEP as a Basic Nuclear Installation (INB), requiring that stringent safety measures be imposed on all aspects of the dismantling. It must remain possible to locate all items of equipment at all times right up until the moment of their destruction; a procedure known as ‘traceability’.

Work begins on dismantling the LEP electron–positron collider to clear the way for the LHC. By the end of the year, almost all LEP equipment had been removed from the tunnel.
An international involvement

Constructing the LHC is a worldwide effort, attracting significant contributions from several major nations outside CERN’s community of 20 Member States. In addition to these important contributions from Canada, India, Japan, Russia and the USA, CERN Host States France and Switzerland also contribute significant additional resources to the LHC, above and beyond their obligations as CERN Member States.

>Canada
The Canadian contribution to the LHC is mainly used to provide hardware to help upgrade the injector chain, particularly the Booster and the PS synchrotron. This involvement goes back to 1995 and is coordinated by the Canadian TRIUMF laboratory.
A second wave of Canadian contribution is mainly for the LHC ring, including 52 twin-aperture quadrupole magnets for beam cleaning insertions, together with power supplies for kicker magnets, pulse-forming networks and switches. Canada will also develop beam-position monitor electronics and carry out some beam optics studies.

>India
The main Indian hardware contribution to the LHC is superconducting sextupole and decapole spool pieces, amounting to half the total LHC requirement for such corrector magnet equipment. In addition, India will supply LHC magnet support jacks and quench heater power supplies.
Circuit breakers are being supplied by Russia, but India remains responsible for the necessary electronics. In addition, India is carrying out several programming and documentation projects.

>Japan
Japan’s early entry into the LHC arena in 1995 provided a memorable boost for the project. Japanese contributions currently total approximately ¥13,850 million (some CHF 160 million). Of this sum, some CHF 25 million was earmarked for constructing the solenoid magnet for the ATLAS experiment. The KEK national laboratory acts as a major coordinator for all of this work.
Japan is the source of much of the basic material (steel and superconducting cable) for the LHC. A further significant Japanese contribution to the LHC is the 16 quadrupoles used to squeeze the colliding beams and boost the interaction rate. Also on the list of equipment are compressors for cooling superfluid helium.

>Russia
The largest and most visible part of the Russian contribution to the LHC is the thousands of tonnes of magnets and equipment for the beamlines to link the SPS synchrotron to the LHC. The supply of this equipment from Novosibirsk is complete (see page 14). Novosibirsk is also supplying insertion magnets for the ring. The Protvino laboratory is responsible for 18 extraction magnets and the circuit breakers that will receive the electronics from India. The Joint Institute for Nuclear Research, Dubna, is contributing a damping system, and a number of other Russian research centres will furnish a range of equipment, including design work, radiation studies, survey targets, ceramic components, busbars and shielding.

>USA
The impressive list of LHC hardware contributed by the USA includes superconducting quadrupoles and their cryostats for beam intersections, superconducting dipoles for beam separation and cryogenic feed boxes. The beam insertion hardware overlaps with that from Japan, and there has been excellent LHC co-operation between these two industrial giants.
Host nations

France and Switzerland, as CERN Host States, make special contributions to the LHC. For France, this includes 218 person-years of work, spread over four major technical agreements, covering the cold mass for LHC short straight sections (handled by the CEA Atomic Energy Commission), the short-straight-section cryostats and assembly (by the CNRS national research agency), calibration of 8000 thermometers for the LHC (by the Orsay laboratory), and design and series fabrication work for the superfluid helium refrigeration system (CEA).

In addition to this national involvement, the local Rhone-Alpes regional government and the départements of Ain and Haute-Savoie also contribute. About 100 person-years of assistance will be supplied by young graduates of technical and engineering universities. Haute-Savoie contributes design work on the integration of microelectronics for the LHC cryogenic system. In addition, the LAPP laboratory in Annecy is developing ultrasonic welding equipment for the superconducting dipole interconnections, and is doing design work for the vacuum chambers of the major LHC experiments. Ain has contributed to a major new construction and assembly hall next to the CERN site. The Swiss contribution comes from the federal government and the canton of Geneva; it covers the cost of a 2.5-kilometre tunnel through which protons will be fed from the SPS to the LHC.

The French Rhone-Alpes region is financing the Rhone-Alpes/CERN programme (PRAC) which contributes to the LHC by providing trained young engineers and technicians, some of whom are seen here on the occasion of a visit to CERN of Anne-Marie Comparini, Présidente du Conseil régional de Rhones-Alpes. Foreground, left to right: CERN Director-General Luciano Maiani; Ernest Nycollin, Président du Conseil général de la Haute-Savoie; Anne-Marie Comparini; Jean Pépin, Président du Conseil général de l’Ain.

Excavation of one of the transfer tunnels to link the 27-kilometre LHC ring with the 7-kilometre SPS ring and through which particles for the LHC will pass. This tunnel (T18) was funded by a special contribution from Switzerland.

The French département of Ain contributed to a special assembly hall for LHC equipment. Thousands of accelerator components will be put together here before being lowered into the LHC tunnel.
A unique feature of CERN is its interlinked network of physics machines, each one feeding the next, providing the world’s longest menu of particle beams. This plurality was not part of CERN’s original plan, but soon became a tradition and a major asset.

CERN’s first major particle accelerator, the PS Proton Synchrotron, began operations in 1959, when for a brief period it provided Europe with the world’s highest energy particle beams. For Europe’s next step, plans for a new synchrotron to attain much higher particle energies initially envisaged a much larger machine built somewhere else, a second CERN. Gradually it became clear that the best plan was instead to build the 7-kilometre ring for the new machine alongside the PS. In this way the 600-metre PS ring could act as an injector, giving the particles a major energy boost before being transferred to their ultimate orbit in the larger ring. The SPS Super Proton Synchrotron, then the largest particle accelerator in the world, supplied its first beams in 1976.

Soon, the SPS was adapted for use as a proton–antiproton collider, and both the SPS and the PS had to learn how to manipulate antiprotons and protons. At the same time, CERN was preparing for its next major physics machine, the 27-kilometre LEP electron–positron collider ring, which meant that the PS and the SPS also had to be adapted for yet another role – the injection system for LEP.

The LHC will need extremely dense proton beams. To continue their roles as injectors, the PS and the SPS have to meet criteria unimaginable when these machines were designed. Adapting the PS, planned in the 1950s, for the particle beams of the 21st century required the introduction and mastery of ingenious and difficult beam handling techniques. After LEP had been decommissioned, it was the turn of the SPS to face the LHC future. For the SPS, 2001 was the year of the ‘big bang’, as the team called their machine’s major overhaul. This involved most of the major SPS accelerator systems, including injection, acceleration, controls and instrumentation, together with major modifications to make existing installations compatible with the new performance levels. Simply to allow this installation work to get under way, 400 SPS main dipole magnets (about half of the total), each weighing nearly 20 tonnes, had to be shifted, together with 200 short straight sections, each weighing 5 tonnes. A complete precision alignment of all machine components was carried out. Later in the year, the completely overhauled and reconfigured machine delivered its first beam at the 450 GeV injection energy required for the LHC and with the required detailed structure for machine commissioning. Attention now turns to increasing beam intensity.

The success of adapting the PS and the SPS for their new roles with the LHC is a tribute both to the foresight of the designers of these now venerable machines and to the continuing ingenuity of CERN’s machine specialists.
Collision course for particle detectors

The very dense beams circulating in the LHC will be brought together 40 million times per second at four collision points spaced around the ring. For these points, huge detectors are being built to take ‘snapshots’ of the produced particles and analyse what happens.

Particle detectors at a colliding beam machine like the LHC usually surround the beam collision point to intercept as many of the emerging particles as possible. They are built in concentric layers, each layer carrying out a special function, such as tracking the different kinds of emerging particles or measuring the energy they carry (calorimetry).

The four major LHC detectors – ATLAS, CMS, ALICE and LHCb – represent the largest particle physics research programme ever, attracting physicists from all over the world. ATLAS and CMS are general-purpose detectors, whereas ALICE and LHCb have more specific physics goals. Most of the physicists working on the LHC experiments come from research institutes in CERN’s Member States; but in addition there are over 500 researchers from the USA, 600 from the Russian Federation, together with large contingents from Canada, China, Eastern Europe, the former Soviet Union, Japan, India and Israel. Development work for these large detectors has been under way for some time. As well as adapting to the sheer scale of the LHC, the experimental teams have to confront new challenges in many areas and have broken fresh technological ground. Major production milestones were achieved in 2001.

ATLAS

In Greek mythology, Atlas was a Titan who supported the heavens. Like its mythological predecessor, the ATLAS detector is huge – 26 metres long, with an outer diameter of some 20 metres, and containing thousands of tonnes of equipment. During 2001, the ATLAS spotlight shifted from the final stages of research and development work to initial fabrication for a wide range of detector components.

Some of these developments are in themselves spectacular. The 5.5-tonne solenoid magnet for the inner tracking detector, developed and built at the Japanese KEK laboratory, arrived at CERN after a long journey by sea, river and road. The next step is integration into the calorimeter barrel-cryostat.

Akira Yamamoto, Solenoid Project Engineer of the Japanese KEK laboratory and ATLAS spokesperson

Peter Jenni with the solenoid magnet for the detector. The 5.5-tonne magnet arrived at CERN on 28 September after a journey half-way round the world.
Another large magnetic component to arrive and be tested is the prototype toroid-magnet coil for the central ATLAS barrel. Already impressive at 9 metres long, eventually it will be dwarfed by the eight 25-metre coils needed for the final detector. The latest prototype is being used to check the various stages of the manufacturing process. The toroid components to equip the end-caps of the detector were another focus of attention during the year.

This 9-metre long toroid, a prototype for the eight 25-metre sections for the main ATLAS magnet, underwent stringent testing at CERN during the year.

Other ATLAS areas where significant production progress was achieved were calorimeter cryogenics and calorimeter components, sensors for the inner tracking detector, and chambers for the muon spectrometer. For the hadronic part of the calorimeter, sub-module production continued in ten different plants around the world. The sub-modules are put together as modules and these in turn are instrumented with optical elements. This alone involved a thousand kilometres of optical fibre and 58 tonnes of scintillator plates. A major challenge in LHC detectors is the electronics, which has to operate inside harsh radiation environments, and design changes have been introduced to enable ATLAS to benefit from the latest developments.

Family photograph of a few members of the ATLAS collaboration at CERN for a meeting.

Modules for the ATLAS 'tile' calorimeter are stored at CERN prior to assembly. Stocks of these modules and of components of other ATLAS detectors are building up at CERN and at regional staging posts around the world.

The ATLAS barrel cryostat at CERN, ready to receive calorimeter modules.
Fitting out a major detector like CMS requires a mass of component equipment, and this acquisition programme gathered momentum during the year, with manufacturing, construction and assembly centres active across the world. The electromagnetic calorimeter will require 78,000 crystals of lead tungstate, a state-of-the-art scintillating material. 9000 crystals for the calorimeter were produced in Russia, and about 10% of the 130,000 avalanche photodiodes for the barrel readout system were supplied.

Equipment for the hadron calorimeter is well advanced, and another impressive sight in the CMS assembly hall was the assembly of the first half-barrel, containing eighteen 30-tonne segments. A sizeable fraction of the chambers for the CMS muon detector endcaps were produced at Fermilab in the USA, and other assembly centres

The LHC takes particle physics into a new dimension of logistics and engineering. CMS stands for ‘Compact Muon Solenoid’, ‘compact’ in LHC terms meaning 21.6 metres long and 14.6 metres across. CMS, as its name suggests, pays a lot of attention to muon detection in the outer layers of the detector, which requires a strong magnetic field inside the detector.

All detector sub-systems have started construction. CMS is being assembled at ground level at LHC Point 5 before being moved into its final position underground, and surface buildings have been completed and handed over.

During the year, the central barrel yoke of the detector magnet gradually took shape in the assembly hall above the LHC ring. The framework for this 14,000-tonne magnet, 13 metres long and six metres across, gives a vivid impression of the new scale of LHC physics. Alongside, the skeleton of one of the two endcaps for the magnet was also assembled. Industrial factories were busy producing the superconducting cable and winding equipment to fit out the magnet.

The 120-tonne inner cylinder, 13 metres long and 6 metres across, of the vacuum tank for the CMS superconducting magnet was hauled up the Jura mountains en route to CERN. The cylinder is the largest single CMS component.

The outer shell of the vacuum tank visible inside the rings of the central barrel of the CMS detector magnet in the assembly hall above the LHC ring.

Assembly of one of the endcaps for the CMS magnet.
in Beijing and St Petersburg are coming on stream. Chambers for the central barrel of the muon detector are being assembled at centres in Spain, Germany and Italy.

### Awards

Construction and supply work for the big LHC experiments is assigned to contractors all over the world. Meeting the LHC’s stringent requirements can be a major industrial challenge.

Another CMS 2001 milestone was completion of the first half-barrel of the hadron calorimeter, containing eighteen 30-tonne segments.

**Award time at ATLAS.** ATLAS spokesmen Peter Jenni (left) and ATLAS Transition Radiation Tracker (TRT) project leader Daniel Froidevaux present an ATLAS supplier award to Patrick and Simon Hester, directors of UK company Lamina Dielectrics, which supplied 180,000 high-tech straws for the ATLAS TRT.

The collaboration building the CMS experiment awarded its highest distinction to two suppliers – the Spanish firm Felguera Construcciones Mecanicas, represented by Ernesto Alvarez (left), and the Japanese firm Kawasaki Heavy Industries, represented by Kazuo Mizuno (right).
ALICE in the nuclear wonderland

About a microsecond after the Big Bang some 12 billion years ago, the Universe was a seething soup of quarks and gluons at a temperature of a hundred billion degrees – almost a million times hotter than the centre of the Sun. As this ‘quark–gluon plasma’ cooled, it eventually froze into protons and neutrons, supplying the raw material for nuclei, which appeared on the scene a few minutes later and became the building blocks for what we see around us.

To check whether our understanding of the Big Bang is correct, since 1986 experiments at CERN have been trying to recreate the first few seconds of the Universe by accelerating beams of nuclei to the highest possible energies and piling them into dense nuclear targets. The hope is that in these collisions, individual nuclei can fuse together to create tiny pockets of the primordial plasma. Any globules of this plasma formed in laboratory experiments would be about the size of a large nucleus, and would quickly evaporate and cool. The events which shaped the early Universe occurred over only a few seconds, but nevertheless spanned an enormous range of temperature as the primeval fireball expanded and cooled rapidly.

In physics, temperature and energy are equivalent – higher temperatures mean that particles move with more energy; cooling down means that particles lose energy. Because of the vast energy–temperature range that needs to be covered, the programme of experiments at CERN using nuclear beams has so far only scratched the surface of the quark–gluon plasma region, seeing the first signs that a new kind of material is being formed. To study these phenomena better and in detail, a new high-energy nuclear collider, RHIC, has begun operation at the US Brookhaven National Laboratory, attaining higher energies and temperatures. To take over the quark–gluon plasma baton from RHIC, CERN’s LHC is also designed to collide high-energy beams of heavy nuclei as well as protons.

The big ATLAS and CMS experiments are designed to monitor these nuclear collisions as well as the usual LHC diet of colliding proton beams. But a separate major experiment, ALICE, is specifically designed to study what happens in the LHC’s nuclear collisions. ALICE will be built at Point 2 in the LHC ring, formerly the home of the L3 experiment at the LEP electron–positron collider, where ALICE inherits the large L3 solenoid magnet. For ALICE this magnet will require major modification.

In 2001, dismantling the rest of the L3 detector was essentially completed, and the experimental area could begin to be prepared for the ALICE era. During the year, ALICE submitted the last of the ten detailed Technical Design Reports needed for official authorization to proceed with the procurement of component equipment, and construction of most of the detector modules has started. The nuclear collisions studied by ALICE will be much more complex than those produced by LHC proton beams. Handling the high data rates for the LHC is already a major challenge, but ALICE will have to contend with hundreds of times more particles. The design of the ALICE data acquisition system has progressed during the year to take account of new developments, and now includes more levels of fast electronics ‘triggers’ to select collision data worthy of further study and streamline the subsequent analysis.

The Time Projection Chamber (TPC) of the ALICE experiment at the LHC has to record the extremely complicated patterns of charged particle tracks produced in high energy nucleus–nucleus collisions. This picture shows the prototype of the field cage of the TPC in which the ionization in particle tracks drifts at constant speed over distances as large as 2.5 m.
Quarks come in six varieties, which can be grouped pairwise into three distinct families. The lightest pair, ‘up’ (u) and ‘down’ (d), makes up the protons and neutrons of ordinary nuclear material. The other two pairs – ‘strange’ (s) and ‘charm’ (c), and ‘beauty’ (or ‘bottom’, b) and ‘top’ (t) – are much heavier, and have to be created by subjecting the lighter quarks to high-energy collisions. Extremely unstable, they quickly decay into lighter quarks.

The study of quarks is a major focus of particle physics research, and all LHC experiments will carry on this tradition. However one LHC experiment will concentrate on the physics of b quarks, hence the name LHCb. Being extremely heavy, b quarks are difficult to produce, and, once produced, are highly unstable, so are difficult to study. LHCb’s task is thus doubly difficult.

High up on LHCb’s agenda is the study of the violation of CP symmetry, a phenomenon which appears to dictate Nature’s preference for matter over antimatter. Until very recently, CP violation could only be studied in the interactions of strange quarks (see page 29).

Unlike the other three major LHC experiments, whose detectors surround the region where the LHC beams collide to catch as many of the produced particles as possible, LHCb will be more selective, concentrating on a small cone around the beam direction, where most of the b quarks are produced.

Of prime importance for LHCb are the silicon vertex locator (VELO) and Ring Imaging CHerenkov counters (RICHs). VELO is a precision high-technology microscope to distinguish the point where the b quarks are produced, and another, several millimetres away, where they subsequently decay. The RICHs will be used to identify emerging particles as protons, kaons, or pions. During 2001, the full VELO and RICH Technical Design Reports (TDRs) were approved, as were the TDRs for major muon and calorimeter detector modules.

Electronics specifications for several triggers to preselect valuable data for subsequent analysis are well defined, and design homed in on a specific solution of silicon sensors for the inner tracker.

A TDR was also submitted for the outer tracker, while Engineering Design Reviews were undertaken for the various LHCb calorimeter modules, and their construction has started.

The LHCb experiment is thus well on the way to becoming a reality.
LHC computing

Testbed for the world

When the LHC comes into operation, each year its four major experiments will accumulate over ten million gigabytes of data, equivalent to the contents of about twenty million CD-ROMs. Handling this will require a thousand times more computing power than is available to CERN today.

Each of the three largest LHC experiments – ATLAS, CMS and ALICE – will require computer power equivalent to 40,000 of today’s PCs. Adding LHCb to the equation gives a total equivalent of 140,000 PCs, and this is only the start. Within about a year of LHC commissioning, this demand will have grown by 30%. Nearly ten thousand scientists, at hundreds of universities around the world, will group in virtual communities to analyse data from the LHC experiments. With users across the globe, this represents a new challenge in distributed computing. CERN’s strategy is the coordinated deployment of communications technologies at hundreds of institutes via an intricately interconnected worldwide grid of tens of thousands of computers and storage devices.

The LHC Computing Grid project will proceed in two phases. The first, activated in 2002 and continuing in 2003 and 2004, will develop the prototype equipment and techniques necessary for the data-intensive scientific computing of the LHC era. In 2005, 2006 and 2007, Phase 2 of the project, building on the experience gained in the first phase, will construct the production version of the LHC Computing Grid.

Phase 1 will require a CHF 30 million (some € 20 million) investment at CERN, which will come from individual contributions from CERN’s Member States and the major involvement of industrial sponsors. Over 50 positions for young professionals will be created in Phase 1 of the project, offering unique opportunities for training and experience. Complementary investments are being made by participants in the LHC programme around the world, particularly in Europe, the USA and Japan.

CERN and its LHC partners will form the first ‘virtual organization’ to adapt Grid technologies to a giant data-intensive, worldwide computing task. The challenge of handling such huge quantities of data will be faced subsequently by governments, commerce and other organizations. The LHC will be a computing testbed for the world.

The LHC Grid

The LHC’s computing requirements arrived on the scene at the same time as a growing awareness that major new projects in science and technology need matching computer support and access to resources worldwide.

In the 1970s and 1980s the Internet grew up as a network of computer networks, each established to serve specific communities and each with a heavy commitment to data processing. In the late 1980s the World Wide Web was invented at CERN to enable particle physicists scattered all over the globe to access information and participate actively in their research projects directly from their home institutes via the Internet. The amazing synergy of the Internet, the boom in personal computing and the growth of the Web grips the whole world in today’s dot.com lifestyle.
However, the Web is not the end of the line. New thinking, summarized in a milestone book entitled "The Grid", by Ian Foster of the US Argonne National Laboratory and Carl Kesselman of the Information Sciences Institute of the University of Southern California, aims to develop new software (middleware) to handle computations spanning widely distributed computational and information resources - from supercomputers to individual PCs.

In the same way that the World Wide Web makes information stored on a remote site immediately accessible anywhere on the planet without the end user having to worry unduly where the information is held and how it arrives, so the Grid would extend this power to large computational problems. Just as a grid for electric power supply brings watts to the wallplug in a way that is completely transparent to the end-user, so the new data Grid will do the same for computer power.

Leading partners

CERN is also the leading and overall coordinating partner in DataGrid, a project spanning a wide collaboration of different sciences, ranging from particle physics to Earth monitoring and biology. DataGrid will receive more than € 9.8 million over three years to develop middleware for implementing different applications over a wide network of computer systems. The project was drawn up in the context of the European Union's Fifth Framework Information Society Technologies programme. For CERN, this programme will integrate well into LHC preparations. Indeed, the model for the data Grid distributed computing architecture is based largely on the results of the MONARC (Models of Networked Analysis at Regional Centres) project. This foresees a major Tier 0 centre at CERN with thousands of communications nodes, connected to regional Tier 1 centres with upwards of a thousand nodes, then Tier 2 centres at university campus level, and Tier 3 centres in research departments.

The DataGrid project set up its first testbed at the end of 2001, linking CERN to other large particle physics computing centres in Italy, France and the United Kingdom. This will be expanded to encompass about 40 sites spread across Europe, providing a giant virtual computer centre for the computer-hungry data challenges of the LHC experiments and other applications in Earth observation and biology. CERN has also set up the 'openlab' for Grid applications, in which leading information technology firms collaborate in the development of advanced distributed computing.

As well as the technology needed to build a Grid of distributed computing centres, new techniques are required for managing the thousands of processors and storage devices that will be installed at CERN and other large centres. New levels of automation will be required to configure, monitor and operate these giant computing fabrics. New techniques must be developed to ensure that any problems are automatically diagnosed and repaired, eliminating to a large extent the need for human intervention.

The DataGrid project serves also to coordinate Grid developments that are going on in many European countries, funded by national research organizations. Another project funded by the European Union and led by CERN, DataTAG, will provide a high-speed network connection to North America which will enable the European DataGrid to work with Grid testbeds in the USA. Particle physics is thus playing a leading role in Grid developments, exploiting its long experience with large-scale computing and high performance networking, while building a global computing facility that will deliver the massive computing power needed for LHC data analysis.

Preparing a computing testbed for the world – CERN's data tape library and control area.
Over several years, the big NA48 experiment at CERN patiently accumulated data from the decays of a special kind of particle, neutral kaons, studying a delicate effect called CP symmetry violation. With exact CP symmetry, right-handed particles behave in the same way as left-handed antiparticles (and vice versa). The idea of CP symmetry was introduced in the late 1950s, when physicists discovered that weak interactions (nuclear beta decays) are not left–right (parity, P) symmetric. In 1964 a landmark US experiment with neutral kaons found that the combined CP (charge/parity) symmetry too was flawed.

In the early 1970s, theoretical physicists discovered that any attempt to describe this mysterious CP violation needed at least six kinds of quark. At the time, only three varieties of quark were known. Physicists realized that they had to widen their horizons, and evidence for additional quarks soon showed up. After having discovered that CP violation occurs, the goal of experiment switched to measuring the effect precisely. As well as underpinning a picture of the underlying structure of the Universe in terms of six quarks, it could also help explain how a Universe apparently composed entirely of matter could have evolved from a Big Bang which initially produced equal amounts of matter and antimatter.

There are two kinds of neutral kaon, one the antiparticle of the other, distinguished only by the obscure quantum number of strangeness (carried by the strange quark). However, strangeness is only conserved in strong interactions, and in weak decays the neutral kaon particle and antiparticle get mixed up. This produces two clearly distinguishable kinds of neutral kaon – one variety that decays relatively easily into two pions and is therefore short-lived, and another that cannot slip easily into two pions and instead has to struggle to decay into three pions. The latter therefore lives longer.

In 2001, a precise measurement was made at CERN of one of the most elusive effects in particle physics. After many years of struggle, with sometimes conflicting results from experiments at different laboratories, the parameter that measures the tiny asymmetry between quarks and antiquarks was fixed confidently.
In 1964, physicists discovered that a few long-lived kaons in every thousand disobey the rules and instead decay into two pions. CP is violated. But there could be a deeper form of CP violation at work. Strongly interacting particles like kaons are built up of quarks. Instead of proceeding simply via the quantum mechanical mixing of neutral kaons, CP violation could also happen in the underlying quark transitions. If so, Nature can distinguish between matter made up of quarks and antimatter made up of antiquarks – the assignment is not mere convention. Such direct CP violation means that the probability of decay is different for particle and antiparticle. It could have occurred immediately after the Big Bang, when subnuclear particles began to freeze out of the primordial quark–gluon soup.

To establish whether direct CP violation occurs and to measure it, physicists must carefully compare two ratios. The first is the rate of long-lived kaons decaying into two charged pions, compared with the decay rate into two neutral pions. The second ratio is the equivalent pion pair comparison for short-lived kaons. If these two ratios are not exactly the same, then the probability of decay into a pair of charged pions is different for neutral kaon particle and antiparticle, and direct CP violation can occur.

Measuring this double ratio accurately is extremely difficult and requires a major physics investment. NA48 used special techniques, and the number of neutral kaon decays collected and analysed was far greater than any other experiment so far.

The parameter used by physicists to measure this CP violation ($\varepsilon'/\varepsilon$) is the difference of the double ratio from unity, divided by a numerical factor. The new NA48 result is $15 \pm 2.7 \times 10^{-4}$, showing much smaller errors than earlier measurements. This shows that direct CP violation certainly happens. The classic indirect CP violation discovered in 1964 occurs in a few decays in every thousand, and for every thousand indirect CP violations there are a few direct CP violations. Nature can thus discriminate between matter and antimatter. The tiny effect of a few per million seen with neutral kaons does not in itself explain the demise of all the Big Bang antimatter. Somewhere else, a much larger effect must happen, but direct CP violation provides at least the tip of the matter iceberg.

A vital part of the NA48 detector is the liquid krypton calorimeter which carries out the difficult task of reconstructing the decays of neutral pions. This photo shows the installation of electronic readout prior to immersing the calorimeter in its cryostat.
The CNGS project is motivated by recent results obtained at the Super-Kamiokande detector in Japan and supported by other experiments which see fewer neutrinos than expected. Explaining this requires new neutrino behaviour, called ‘neutrino oscillation’. Classically, neutrinos come in three varieties – electron, muon and tau, depending on their partner particles. These neutrino varieties are supposed to be immutable, so that a neutrino created with a muon should remain a muon neutrino for ever. However, experiments monitoring the arrival of neutrinos produced in the atmosphere by cosmic rays have suggested that some muon-type neutrinos are ‘lost’. To account for this deficit, some neutrinos that start off muon-like could transform (‘oscillate’) en route into tau-like particles.

To maximize the chances of seeing such an effect, the experiment needs a long baseline, in this case the 730 km between CERN and the Gran Sasso laboratory. The neutrino beam, starting off purely muon-like as it left CERN, would contain tau neutrinos by the time it arrives at Gran Sasso. When they interact, these tau neutrinos can produce highly unstable tau leptons, which decay within 1 mm of the neutrino interaction point, producing a characteristic kink in the decay path.

At CERN, the CNGS project involves a major civil engineering effort, being undertaken by an international consortium. After excavation of a 55-metre vertical access shaft, the assembly cavern for the tunnel boring machine has been built. About three kilometres of tunnels and caverns – some 45,000 cubic metres of rock – had to be excavated, of which about half had been accomplished by the end of the year.
For more than 30 years, CERN’s unique ISOLDE on-line isotope separator has made important contributions to nuclear physics, providing also a valuable counterpoint to CERN’s main research programme in high energy physics.

For the future, CERN’s tradition in nuclear physics is set to continue with a new nuclear physics facility, REX-ISOLDE, commissioned at the end of October 2001. REX-ISOLDE builds on CERN’s existing radioactive beam facility, taking radioactive nuclei and boosting them to higher energies, opening up new horizons for the laboratory’s substantial nuclear physics community. REX-ISOLDE is built around a new linear accelerator, funded and constructed by a broad European collaboration.
The human factor

The human factor is a key element in the scientific successes of the laboratory. CERN has been able to rely on highly competent and motivated staff. Today, many of them are reaching the end of their career and will retire in the coming years. In fact a large fraction of staff who built and operated the SPS and LEP machines and detectors have already retired and their activities have been taken over by newly recruited younger staff. In the past five years, 908 people left and 699 joined the organization.

The jobs of many staff changed drastically in 2001: they dismantled the LEP collider and are now heavily involved in the construction of the LHC, working under tight schedules with industry, which is supplying many components. Budget reductions require that during the LHC-construction phase staff numbers will decrease further from 2663 at the end of 2001 to reach 2040 in 2006. With over 600 people expected to retire between 2002 and 2006, this reduction is fully absorbed. However, staff recruitment will slow considerably in this period.

This generation and activity change, combined with the perspective of a leaner organization, called for a series of innovative human resources measures. The examples below, taken from different domains, illustrate how CERN has reacted positively.

New career policy

Policies for managing individual careers and reward were reviewed and in September 2001 MAPS (Merit Advancement and Promotion Scheme) was introduced. The main new features include:

- critical reviews at several stages in a career;
- modulation of advancement at the different stages in a career;
- introduction of allowances linked to performance, responsibility and specific labour market situations.

As such, MAPS aims to achieve a more dynamic career structure with more flexible possibilities to modulate advancement and reward for individual and team performance.

Long-term care

As an international organization, CERN has its own social security system. The increase in the number of people who are no longer able to function independently in daily life, which comes with an increased lifespan, is a serious threat for its financial equilibrium. Those people need assistance over an extended period, which they used to find through expensive hospitalization. With the introduction of financial support for specialized assistance, financed by a predicted increase in the contributions of the members, CERN’s health insurance scheme will be able to support the 250 dependency cases estimated for 2026.

Short-term personnel

In 2001, approximately 600 people from all over the world came to CERN through the Fellow, Associate and Student programmes to participate in challenging research, development and high-tech activities. This represents a 10% increase compared to 1999, while the budget was not increased. This was only possible through a major effort to establish collaboration agreements funded by outside sources. A good example is the Grid project, where several countries provide financing for 40–50 positions for LHC computing in the period 2002–2004.

New blood. As veterans leave the organization, CERN has been recruiting new staff. Several such group photographs were taken during the year.
Boost for cancer therapy

The LIBO (Linac Booster) was tested during the year. LIBO is a prototype machine for producing particle beams for cancer therapy. Therapy using these beams is able to reach deep tumours without damaging surrounding tissue. The accelerator expertise at CERN is invaluable for developing these new facilities.

Intense antimatter

One of the few places in the world where physicists can study the behaviour of particles of nuclear antimatter. CERN’s AD Antiproton Decelerator provided more intense beams of antiprotons for physics experiments in 2001.

Swiss school

An impressive backdrop at the 2001 European School of High-Energy Physics, held at Beatenberg in the Swiss Bernese Oberland, and organized by CERN. On the left loom the Eiger and Mönch peaks, with the Jungfrau summit obscured by a small cloud.

Expertise for export

A great success at CERN is the EDH Electronic Data Handling system, which has revolutionized CERN’s administrative procedures and greatly reduced paperwork. EDH was sold during the year to a specialist software house. Seen here is the CERN EDH team – left to right, Derek Mathieson, Rótsislav Titor, Per Gunnar Jonsson, Ivica Dobrovicova and James Purvis. Missing from the photo is Jurgen de Jonge.
Honorary doctorates
Steve Myers (left) and Albert Hofmann were awarded the degree of Doctor Honoris Causa by the University of Geneva in recognition of their services to accelerator physics and their essential contributions to the success of CERN's LEP electron-positron collider.

Best craftsman
Didier Lombard of CERN's manufacturing facilities group earned the title of 'Meilleur Ouvrier (Best Craftsman) de France' for his steelwork.

Retirement
Helga Schmal, seen here with Director-General Luciano Maiani, retired after being head of the Director-General's office for four generations of CERN management, with an interim spell as head of the Council Secretariat.

Legion of Honour
Before retiring from the Organization, CERN legal counsel Jean-Marie Dufour (right) became a Chevalier of the French Legion of Honour, receiving the award from French Ambassador to the UN in Geneva and delegate to CERN Council Philippe Petit.

S of the year
French trade show
A regular feature of life at CERN are the periodic trade shows where Member States show their latest equipment and technology. In June 2001 it was the turn of France. Seen here at the inauguration of the 'France at CERN' exhibition are (left to right) Jean-Claude Brisson, French Delegate to the Finance Committee and industrial liaison officer; Florence Carouge of CFME/ACTIM; Philippe Petit, Ambassador and Permanent Representative of France to the United Nations in Geneva; CERN Research Director Claude Détraz; Alexandre Defay, Technical Adviser to the French Minister for Research; Bernard Frois, Director, Department for Energy, Transport, Environment and Natural Resources, French Ministry for Research; and Jean-Jacques Aubert, Director of the IN2P3 research organization and delegate to CERN Council.

German trade show
Later in the year it was Germany’s turn. Seen here at the inauguration of the 'Germany at CERN' trade show in November are (left to right) Karl-Heinz Kissler, Head of CERN's Supplies, Procurement and Logistics Division; Bettina Schöneseiffen, representing the Ministry of Education and Research; Walter Lewalter, Ambassador and Permanent Representative of Germany to the United Nations in Geneva; Maximilian Metzger, also representing the Ministry; and CERN Director Hans Hoffmann.

Intergovernmental research
As well as a scientific laboratory, CERN is a centre of knowledge and expertise. A new departure during the year was a meeting of EIROFORUM, whose primary goal, as part of the European Intergovernmental Research Organization, is to play an active and constructive role in promoting the quality and impact of European research. Attending the meeting at CERN were (left to right) Jerome Pamela of EFDA (European Fusion Development Agreement) and Associate Leader for JET (JET-EFDA); Colin Carlile, Director-General of the Institut Laue-Langevin (ILL), Grenoble; Achilleas Mitasos, Director-General of Research, European Commission; Luciano Malani, Director-General of CERN; Catherine Cesarsky, Director-General of the European Southern Observatory (ESO); Fotis Kafatos, Director-General of the European Molecular Biology Laboratory (EMBL); William G. Stirling, Director-General of the European Synchrotron Radiation Facility (ESRF); and Jean-Pol Poncelet, Director of Strategy and External Relations, European Space Agency (ESA).
International Conference

In September, CERN hosted in Geneva the 17th International Conference on Magnet Technology, which attracted delegates from all over the world. The development and manufacture of magnets for the LHC provided a natural focus for the meeting.

CERN's VIP visits are handled by Wendy Korda (right) and Stéphanie Molinari.

Belgian trade show

Croatia

12 February - Hrvoje Kraljević (left), Croatian Minister of

United States

28 February - US Ambassador to Switzerland Richard Frederick (left) with CERN Director-General Luciano Maiani.
...VISITS

›Israel

16 May - Israel’s Minister of Health Nissim Dahan (centre) at the headquarters of the ATLAS experiment for the LHC with (left to right) Jim Allaby, CERN coordinator for non-Member State affairs; ATLAS experiment spokesman Peter Jenni; Bracha Regev, Chief Scientist, Israeli Ministry of Health; the Minister; Boaz Leshy, Director-General, Israeli Ministry of Health; CERN Director Hans F. Hoffmann and senior ATLAS physicist Giora Mikenberg.

›Romania

30 March (top) - Romanian Minister of Foreign Affairs Mircea Dan Geana signs CERN’s VIP visitors’ book. Alongside is Anda Filip, Ambassador and Permanent Representative of Romania to the United Nations. Later in the year it was the turn of the Romanian President. On 12 October President Ion Iliescu signed CERN’s VIP visitors’ book, watched by CERN Director-General Luciano Maiani.

›Serbia

8 June - Dragan Domazet, Minister of Science, Technology and Development, Republic of Serbia.
Great Britain
30 October - British Ambassador to Switzerland Basil Eastwood with CERN Director-General Luciano Maiani.

Yugoslavia
29 November - visiting the cavern for the ATLAS experiment at the LHC are (left to right) Hans Höfer of ETH Zürich, CERN Research Director Roger Cashmore, 1976 Nobel Prize winner for Physics Samuel C. C. Ting, and Lei Gang, Secretary to the Minister.

Iran
5 July - Iranian Minister of Science, Research and Technology Mostafa Moin (right) and CERN Director-General Luciano Maiani sign a draft memorandum of understanding covering the participation of Iranian universities in CERN’s research programme.

Czech Republic
7 September - Eduard Zeman (left), Minister of Education, Youth and Sport, Czech Republic, at CERN's permanent Microcosm exhibition. Ivan Lehraus, Committee for Collaboration of the Czech Republic with CERN explains. On the right is Milan Hovorka, Ambassador and Permanent Representative of the Czech Republic to the United Nations in Geneva.

Montenegro
7 September - Predrag Ivanovic, Minister of Education and Science, Montenegro (left) with CERN Research Director Roger Cashmore.

China
7 September - Wang Libeng, Minister of Aviation of the People’s Republic of China, and President, China Aerospace Science & Technology Corporation (second from left) with (left to right) Hans Höfer of ETH Zürich, CERN Research Director Roger Cashmore, 1976 Nobel Prize winner for Physics Samuel C. C. Ting, and Lei Gang, Secretary to the Minister.

Yugoslavia
29 November - visiting the cavern for the ATLAS experiment at the LHC are (left to right) Torsten Åkesson, deputy spokesman of the ATLAS experiment; Dragoljub Popovic, Ambassador of the Federal Republic of Yugoslavia to Switzerland; Simone Hajos, Project Engineer, LHC civil engineering; Peter Ažić, Chairman of the Committee of the Republic of Serbia for relations with CERN.
Signatures of the Invisible, an art exhibition inspired by CERN and its work, opened in London in March. The result of a close collaboration between CERN and the London Institute, a premier art and design school, the exhibition was the first public showing of a unique exchange of ideas between artists and physicists. Later in the year, the exhibition visited Tshinghua University, Beijing, and Rome’s Complesso del Vittoriano.

CERN’s workshops put the finishing touches to the ‘spinning tops’ features of French artist Jerôme Basserode.

Paola Pivi’s “Moving needles” is admired at the London opening of Signatures of the Invisible.

Ken McMullen’s “Crumple theory” was turned from paper to metal at CERN.
Frans Heyn 1944–2001
Frans Heyn, who died on 29 December, was named Netherlands Finance Committee delegate in 1976, and Council delegate in 1980. In 1981 he came to CERN as Director of Administration, and in 1990 became Leader of the new Administrative Services Division. As Adviser to several Directors-General, he had special responsibility for CERN liaison with Brussels and with the countries of the former Soviet Union.

Theodore Kouyoumzelis 1906–2001
Theodore Kouyoumzelis, who died on 4 October at the age of 95, was a pioneer of nuclear and particle physics in Greece. He first represented his country at a CERN Council meeting in 1952 and served as Vice-President of CERN Council from 1972–1975. With major responsibilities in Greece, he made significant contributions to his country's physics effort and progress.

Douglas Morrison 1929–2001
Douglas Morrison, who died on 25 February, came to CERN in 1956 and went on to found major international collaborations, mainly in bubble chamber physics. He founded the journal Nuclear Physics B and helped pioneer holographic techniques for bubble chambers. A scientific purist, he was highly critical of what he called ‘pathological science’.

André Rousset 1930–2001
André Rousset, who died on 1 July, came to CERN in 1969 to lead work on new heavy-liquid bubble chambers, and went on to manage the commissioning of the Gargamelle chamber, of which he had been one of the major constructors, under André Lagarrigue. This historic chamber was the scene of CERN’s 1973 discovery of the weak neutral current. After leaving CERN in 1974, Rousset took on major advisory roles in government and in industry.

Fritz Schmeissner 1915–2001
Fritz Schmeissner, who died on 12 April, was the father of CERN’s cryogenic engineering. Arriving at CERN in the late 1950s, he worked on a liquid hydrogen bubble chamber. His cryogenics activities went on to cover larger bubble chambers, liquid deuterium targets, and a superconducting radiofrequency beam separator cooled by superfluid helium. This prepared the way for subsequent large-scale cryogenics applications for LEP and for the LHC.

Christoph Schmelzer 1908–2001
Christoph Schmelzer, who died on 10 June, was a pioneer of German particle accelerators and of CERN. During the construction of CERN’s PS synchrotron in the 1950s, he was deputy to project leader John Adams and helped mastermind the innovative radiofrequency techniques needed to accelerate the PS beams. After leaving CERN in 1959, he went on to help found the German GSI laboratory in Darmstadt.

Miss Steel, as she was universally called at CERN, died on 10 November. A special person, she joined CERN administration in 1955 after harrowing international experience in refugee work, and went on to take care of organizing international physics conferences, first for CERN and subsequently further afield.
Official information and statistics

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BELGIUM / Mr P. Levaux
Professor F. Verbeure

BULGARIA / Professor I. Damianov
Professor J. Stamenov

CZECH REPUBLIC / H.E. Mr M. Hovorka
Professor J. Niederle

DENMARK / Professor O. Hansen
Mr M. Bovbjerg

FINLAND / Professor J. Hattula
Professor R. Nieminen

FRANCE / H.E. Mr B. Kessedjian
Professor J.-J. Aubert

GERMANY / Professor G. Flügge
Dr H. Schunck

GREECE / H.E. Mr M. Karaitidis
Professor E. Floratos

ITALY / H.E. Mr A. Negrotto
Cambiaso
Professor E. Iarocci

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Professor W. Hoagland

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Professor E. Osnes

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Professor R. Sosnowski

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Professor A. Policarpo

POLAND / Professor I. Halliday
Dr F. Saunders

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Professor J. Pisút

SPAIN / H.E. Mr J. Pérez-Villanueva y Tovar
Dr M. Aguilar-Benítez

SWEDEN / Dr M. Johnsson
Professor M. Larsson

SWITZERLAND / Mr Ph. Joye
Professor R. Eichler

UNEDITED KINGDOM OF GREAT BRITAIN & NORTHERN IRELAND

OBSEVERS

Israel / Japan / Russian Federation / Turkey / USA / European Commission / UNESCO
... and its Committees

Committee of Council

President of the Council
Professor M. Bourquin (Switzerland)

Vice-Presidents of the Council
Dr H. Schunck (Germany)
Professor R. Sasnowski (Poland)

Chairman of the Scientific Policy Committee
Professor G. Kalmus (United Kingdom)

Chairman of the Finance Committee
Mrs B. Sode-Mogensen (Denmark)

Members
H.E. Mr H. Kreid (Austria)
Mr P. Levaux (Belgium)
Professor I. Damianov, Professor J. Stamenov (Bulgaria)
Professor J. Niederle, H.E. Mr M. Hovorka (Czech Republic)
Mr M. Bovbjerg (Denmark)
Professor J. Hattula, Professor R. Nieminen (Finland)
H.E. Mr B. Kessedjian, Professor J.-J. Aubert (France)
Professor G. Flügge (Germany)
Professor E. Floratos (Greece)
Professor J. Zimányi (Hungary)
Professor E. Iarocci, H.E. Mr A. Negrotto Cambiaso (Italy)
Mr J. Bezemer, Professor W. Hoogland (Netherlands)
Dr L. Westgaard, Professor E. Osnes (Norway)
Professor J. Niewodniczanski (Poland)
H.E. Mr A. de Mendonça e Moura (Portugal)
H.E. Mr K. Petöcz, Professor J. Pisút (Slovak Republic)
H.E. Mr Perez-Villanueva y Tovar, Dr M. Aguilar-Benitez (Spain)
Professor M. Larsson, Dr M. Johnson (Sweden)
Professor R. Eichler, Mr Ph. Joyce (Switzerland)
Dr F. Saunders, Professor I. Halliday (United Kingdom)

Invited
Professor L. Foà invited in his capacity as Chairman of the European Committee for Future Accelerators

Also present
Director-General: Professor L. Maiani

Scientific Policy Committee

Chairman
Professor G. Kalmus (United Kingdom)

Members
Professor R. Barreiro
Professor W. Buchmüller
Professor P. Carlson
Professor J. Feltesse
Professor J. Friedman
Professor K. Gaemers
Professor A. Golutvin
Professor R. Klanner
Professor S. Ozaki
Professor G. Ross
Professor K. Rybicki
Professor J. Stachel
Professor P. Stralin
Professor D. Trines
Professor S. Yamada

Ex officio members
Chairman of the LHC Experiments Committee:
Professor J.J. Engelen, Professor M. Calvetti (after 1/11/2001)
Chairman of the SPS and PS Experiments Committee:
Professor K. Königsmann
Chairman of the LEP Experiments Committee:
Professor M. Spiro
Chairman of the LHC Machine Advisory Committee:
Professor M. Tazzari, Professor M. Tigner (after 1/11/2001)
Chairman of the ISOLDE and Neutron Time-of-Flight Experiments Committee:
Professor H. Flocard
Chairman of the European Committee for Future Accelerators:
Professor L. Foà

Also present
President of the Council:
Professor M. Bourquin (Switzerland)
Chairman of the Finance Committee:
Mrs B. Sode-Mogensen (Denmark)
Director-General: Professor L. Maiani

Finance Committee

Chairman
Mrs B. Sode-Mogensen (Denmark)

Members
One or more Delegates from each Member State
Personnel statistics 2001
(end of year figures)

Evolution of staff numbers

<table>
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<th>Year</th>
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<th>2000</th>
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Evolution of Fellows, Associates and Students

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CERN staff

- Research physicists: 3.3%
- Technical staff: 9.2%
- Applied scientists and engineers: 16.6%
- Manual workers and craftspeople: 36.7%
- Administrators and office staff: 34.2%

Financial statistics 2001
Percentage contributions of Member States
As per Budget document CERN/FC/4302

<table>
<thead>
<tr>
<th>Country</th>
<th>Contribution</th>
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<tbody>
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<td>Austria</td>
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<tr>
<td>Belgium</td>
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<tr>
<td>Bulgaria*</td>
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<tr>
<td>Czech Republic</td>
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<tr>
<td>Denmark</td>
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<td>Finland</td>
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<td>France</td>
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<td>Germany</td>
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<tr>
<td>United Kingdom</td>
<td>17.66</td>
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</tbody>
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* Following the Council Resolution of March 2001 (CERN/2369), the Bulgarian contribution is limited to 934 kCHF (0.10%).

** Following the Council Resolution of June 1999 (CERN/2286), the Greek contribution is limited for 2001 to 9 MCHF (at 1999 prices).
### Expenditure statistics 2001

Total expenditure for 2001 was 1,059.3 million Swiss francs. The breakdown of expenditures is as follows:

- **Personnel**: 44.5% (44.5% of total expenditure)
- **Debt repayment**: 2.3% (2.3% of total expenditure)
- **Energy**: 2.4% (2.4% of total expenditure)
- **Materials (non-LHC)**: 22.0% (22.0% of total expenditure)
- **Materials LHC project, operation and detectors**: 28.8% (28.8% of total expenditure)

#### Breakdown by Headings and Totals

| Headings                      | Totals  | Directorate-General, Directorate Services Unit | Divisions | Energy | Debt Repayment |
|-------------------------------|---------|-----------------------------------------------|-----------|--       |                |
| Totals 2001                   | 1,059,344 | 25,104 | 63,690 | 265,967 | 384,590 | 270,443 | 24,929 | 24,622 |
| 1. Personnel                  | 471,296 | 9,315 | 55,840 | 164,876 | 154,356 | 86,909  | -      | -      |
| 2.6.3. Materials              | 563,426 | 15,788 | 7,849  | 101,091 | 230,234 | 183,534 | 24,929 | -      |
| 2. Operating Expenses         | 232,496 | 14,402 | 6,188  | 47,449  | 70,786  | 68,750  | 24,920 | -      |
| 3. Supplies                   | 330,930 | 1,386 | 1,661  | 53,641  | 159,448 | 114,784 | 9      | -      |
| Debt Repayment                | 24,622  | -     | -      | -       | -       | -       | 24,622 |        |

(figures rounded to the nearest thousand Swiss francs)