The division’s main focus in 2000 remained the final definition, industrialization, and procurement of components for the main accelerator systems of the LHC, i.e. superconducting magnets and their ancillaries, cryogenics, vacuum, and industrial controls. As an illustration of this intense activity, it is worth mentioning the 14 engineering design or production-readiness reviews held over the year, as well as the 34 additional contracts submitted for adjudication to the Finance Committee, for an overall value exceeding 300 MCHF. The division also continued to provide full support to the operation, development, and upgrade of the cryogenic and vacuum systems of the CERN accelerators and physics experiments, a particularly demanding task in this final year of LEP operation at very high energy. The activities of the eight technical groups are reported in detail in below.

Cryogenics for Accelerators

Cryogenics for LEP and SPS

The final intervention on the refrigerator at Point 4 of LEP for the cooling capacity upgrade was successfully done during the 1999/2000 shutdown and the achieved capacity enabled LEP to run reliably with all four cryoplants.

Although the clogging phenomenon of the turbine filters, especially in two plants, could be reduced after an extensive cleaning of the circuits, it still could not be eliminated and caused some downtime. Nevertheless, the constant follow-up of the problem and co-ordination with the operation team allowed the optimization of the LEP running time for machine development and high-energy physics time.

To avoid any oil leakage from the compressor circuits to the environment, the compressor buildings were modified in order to act as possible oil retention ponds. The excellent performance of all accelerator systems allowed LEP to run reliably up to an energy of 104.5 GeV. The running of the cryogenic systems of LEP and SPS were very successful. The number of cryogenics availability hours lost resulted in a mere 1.98% loss of LEP 2000 running time, to be compared with the 3.68% lost in 1999.

After the announcement of the decision to stop LEP, the plan for the dismantling, prepared beforehand, started with the safety measures necessary to ensure safe dismantling. First cuts on the cryogenic equipment were already performed in 2000 to prepare dismantling in 2001.
Cryogenics for the LHC

It was decided to install the LHC full test-cell in SM18 (String 2) in two phases, firstly with two quadrupoles and three dipoles until May 2001 and secondly with all machine elements needed for a full cell beginning of 2002. In addition to the cryogenic infrastructure such as liquid helium supply lines, distribution box and a quench buffer volume already installed and commissioned, cryogenic equipment is needed to cope with the partial set-up of the String 2 assembly.

After an upgrade of the cryogenic infrastructure for the magnet test plant in SM 18 with the installation and commissioning of all sections of a new compound cryogenic distribution line to serve up to twelve test sites, several departures of this line were used to serve installed magnet test stands or temporary cryogenic test facilities such as the US-supplied experimental set-up for testing the heat exchange of the future cryo-loops for the inner triplets or the Cryolab Large Test Facility (CLTF).

Two Cryogenic Feeder Unit prototypes (CFUs), are now fully operational for the series testing of LHC dipoles and quadrupoles. The original contract which also included the delivery of the series CFUs was terminated and new contracts for 12 Cryogenic Feed Boxes (CFBs), of final design and their cryogenic current leads, were awarded to an expert firm. The first two CFBs are scheduled to be delivered in 2001.

To cool the magnets to the required very low temperature, eight 2.4 kW at 1.8 K helium refrigeration units using cold hydrodynamic compressors are being manufactured by IHI/Linde (Japan/Switzerland) and Air Liquide (France). The units will be delivered from spring 2001 onwards, technically validated on a cryogenic test stand before being installed underground and linked to the different 4.5 K cryoplants. The cryogenic infrastructure for the test stand in the P1.8 area and the link to the neighbouring cryoplant as well as the associated control system were undertaken.

The manufacture of the four new large helium refrigeration plants for the LHC, each of an equivalent cooling capacity of 18 kW at 4.5 K is well in hand. The helium compressor station of the first plant has been installed in point 1.8 and first test runs were made. Buildings to house further helium compression stations and cold boxes are nearly finished or will be finished after shutdown of the LEP cryoplants. Pipe-work for gaseous helium and cooling water for all surface sites and shafts was contracted to industry.

For the partial storage of the helium inventory and possible gas recovery from magnet quenches, 20 out of the 30 pressure vessels (250 m$^3$ at 2 MPa) ordered were installed and pressure tested, monitored by acoustic emission, in addition to the 12 vessels recovered from LEP. The remaining 10 tanks as well as an additional 10 vessels recently ordered will be delivered in 2001/2002.

Ten 50 000-litre liquid-nitrogen storage tanks were ordered. They will be installed at the five cryogenic sites around the LHC and serve the refrigeration plants and their full-flow dryers as liquid nitrogen buffer volumes.

A major item of the cryogenic system still to be procured is the Cryogenic Distribution Line (QRL) running in parallel to the magnet cryostats, feeding all cryogenic consumers with helium at different temperatures around the whole machine circumference. As an intermediate milestone in the procurement procedure of the line, qualifying pre-series test cells of approximately 110 m length were delivered and
installed on a test stand at CERN for extensive testing, before final tendering with the qualified firms for the total QRL of 26.7 km length. Qualification tests on two test cells were done and the third one will be finished by March 2001 followed by the final tendering. This phase will be concluded by critical design reviews.

The procurement procedure for five cryogenic interconnection boxes linking all main cryogenic components to the cryoplants and distribution system is engaged.

After prototyping of cryogenic components such as superfluid helium relief valves, sub-cooling heat exchangers, flow-meters and flow regulated control valves, final technical specifications were written and the procurement procedures partly launched.

High-accuracy cryogenic temperature sensors are needed for the precise measurement of the magnet cold mass temperatures. Six thousand of them were ordered and 15% already delivered. Their signal conditioners as well as prototype pressure transducers, which have to withstand the working conditions of the machine tunnel, are still under irradiation tests.

The PLC-based industrial process control system, UNICOS, and its associated software for the control and supervision of the cryogenic equipment of the LHC accelerator and the LHC experiments were ordered from industry within the estimated budget. The objective is to ensure a homogeneous support and maintenance policy aiming at an operation of the different cryogenic systems by a single team.

**Cryogenics for Experiments and Test Areas**

**Cryogenic Support for LEP2 and Fixed-Target Experiments**

In the SPS North Area, helium refrigeration was supplied to three experiments using superconducting detector magnets: NA49 (two magnets), CMS-RD5, and ATLAS-H8. Total operation time was 10 000 hours.

For LEP2 experiments, DELPHI and ALEPH superconducting solenoids with the associated low-β quadrupoles completed their last physics run and the two cryogenic plants, operated for more than 100 000 hours over the last 12 years, are now being dismantled.

Liquid helium and liquid nitrogen cryogenics were upgraded for the COMPASS experiment in order to be ready for first operation in 2001.

For the new CAST experiment, preliminary studies were carried out in order to evaluate the cryogenic needs. The DELPHI cryogenic plant will be re-installed at the surface of LHC Point 8, providing the required 4.5 K cooling capacity.

**Cryogenic Support for LHC Experiments**

**CMS experiment** The external cryogenic plant (supplied by Air Liquide) for the large superconducting solenoid is under construction, and delivery and commissioning of the first components is expected in 2001.
Layout and integration studies together with all the necessary infrastructure facilities were completed for testing the entire plant at the surface of LHC Point 5 prior to the commissioning of the magnet.

**ATLAS experiment** The ECR group continued to provide technical support for the operation of three test benches running on the H6 and H8 beams of the EHN1 experimental hall for testing the prototype and pre-series modules of the liquid argon calorimeters.

The helium cryogenic facility in the West Area (Bldg. 180) for testing the superconducting toroids of the barrel magnet was completed and almost entirely commissioned. First operation of a prototype model magnet (B00) powered via 20 kA current leads was achieved. The cryogenic infrastructure is now ready for allowing testing in 2001 of the B0 prototype magnet delivered at the end of 2000.

Detailed studies were pursued to provide, in the same area, a large test facility for the final liquid argon calorimeters (barrel and end-caps) and the central solenoid.

The design of the common external cryogenic system of the ATLAS magnets at LHC Point 1 is completed and a technical specification for a new cryoplant prepared.

Support was given in the design of the proximity cryogenic system for the toroidal magnets (barrel and two end-caps) in close collaboration with RAL.

Advisory work was provided to KEK for the proximity system of the central solenoid. Much effort was devoted to co-ordinating and supervising the collaborations established with several external institutes for the cryogenics of the liquid argon calorimeters namely:

- BNL (USA) for the nitrogen refrigeration system,
- LAL (Orsay) for the control system,
- ISN (Grenoble) for the proximity cryogenics,
- NTNU (Norway) for the liquid argon and liquid nitrogen dewars.

The integration and the design studies followed by the preparation of a technical specification of the majority of the final components were completed.

**Cryogenic Support for Test Facilities of LHC Magnets and RF Cavities**

In 2000, the ECR group continued to operate three test facilities for the cryogenic components of the LHC.

1) The SM18 large area with two 6 kW helium refrigerators (Air Liquide and Linde plants) with the associated recovery and purification units. Total running time was 8000 hours (84% Air Liquide plant). This facility supplied liquid helium to:

- the LHC full-sized magnets test benches and LHC R&D test area;
- the test benches of superconducting cavities for both the LHC and other future accelerators;
1) mobile dewar (10 000 litres) filling station. Total number of dewar deliveries is 29 with an average filling of 7000 litres.

A technical specification was prepared for a 250 m long transfer line, which will make the link with the first new LHC large cryoplant of 18 kW at 4.5 K, so as to increase the liquid helium production in the SM18 area.

2) The Bldg. 892 test area for short model magnets where a new helium distribution valve box was designed and is now under construction.

3) The Bldg. 163 area for the tests of LHC superconducting cables. This facility was extensively operated for the first time during 5000 hours.

Central Cryogenic Laboratory

The activities of the Central Cryogenic Laboratory (Cryolab) on R&D work for CERN-wide cryogenic applications include small-sized thermal, hydraulic and electrical tests in a cryogenic environment, the conception and design of cryostats for special customer applications, calculation of thermal and hydraulic systems, advisory work in reviews of technical specifications, and participation in design working groups. During 2000, 18 experimental projects were run by the Cryolab, of which 10 continued from the previous year. In addition, 13 tests, of which 5 continued from the previous years, received the active support of the Cryolab but were run directly by the customers. A full-scale (15 m long) test facility reproducing the same pattern of temperature levels as the LHC dipole cryostat was constructed and operated in SM18 to measure the corresponding heat loads down to 1.9 K. As every year, the practical part of one cryogenics course and two safety courses were held at the Cryolab, confirming its role in training and education in cryogenics.

Supply of Cryogenic Fluids on Site

The central liquefier totalled 6000 hours of running time, with 240 000 litres of liquid helium distributed via mobile dewars to about 40 customers. The recently installed helium recovery and purification plant with 400 Nm³/hr capacity, associated with the central liquefier, was extensively operated recovering 600 000 Nm³ of helium. A new liquid helium buffer dewar of 5000 litres was installed in parallel to the upgrading of the gaseous helium recovery system which was linked to the existing facilities in the West Area.

5400 tonnes of liquid nitrogen were supplied to the various users to 19 large liquid nitrogen storage dewars in operation on the CERN site. The upgraded safety devices (closing valves against excess fill) of the dewars performed well.

A technical specification was prepared for the supply, over the next three years, of the helium required by the operation of CERN-wide facilities.
Operation of CERN-Wide Cryogenics

A technical specification was completed and the corresponding contract covering the CERN needs over the next four years was assigned to the Air Liquide/Linde/Serco consortium.

Main Magnets and Superconductors

Superconducting Cables

The procurement of the niobium–titanium alloy bars and of the niobium sheets for the three European strand manufacturers is progressing well according to schedule. Close to 28% and 33% of the total quantities of niobium–titanium alloy bars and niobium sheet, respectively, were delivered. The superconducting (SC) strand manufacturers completed the upgrade of their manufacturing facilities necessary to cope with the required large-scale production of uniform quality. They also substantially increased their staff.

The series production of the two SC strand types (type 1 and type 2) started at the premises of two European contractors and of the Japanese one. About 4.3% and 2.3% of the respective total strand 1 and strand 2 quantities were produced. These quantities correspond to 242 unit lengths of cable 1 and 141 unit lengths of cable 2 (four unit lengths of each cable type are necessary for one double-aperture dipole magnet). The other two contractors show some delay in their strand fabrication schedules.

In the companies that have started their cable deliveries, a few billets were rejected on account of strand breakages. The breakage of strands during manufacturing (a difficulty affecting the overall production yield) was addressed by the firms through a systematic effort to avoid contamination by foreign particles at critical manufacturing steps. A reduction of the number of breakages was achieved, but further efforts are needed. The specified physical and dimensional SC strand characteristics are achieved regularly, although it appears that the residual strand magnetization must be closely monitored in order to minimize field imperfections in the LHC.

The full control of the industrial coating process and of the heat treatment of the finished cable, necessary to achieve the required inter-strand contact resistance in the cable, was achieved in three companies.

The implementation of statistical quality and process control procedures, at the various steps of fabrication, is progressing well.

Two cabling machines are running regularly with two or three production shifts. The running-in of the third cabling machine, which has been designed for high productivity, is progressing. In 2000, it was possible to deliver cables for the first 18 pre-series dipole magnets (1.5% of the total quantity) to the cold mass contractors.

The SC strand and cable test facility at CERN is operational and ready to cope with the large number (up to 30 000 per year) of various measurements of physical and dimensional characteristics. These measurements are part of the contractual acceptance tests agreed between CERN and the five SC cable suppliers.
Short Model Dipole Programme

The 1 m long dipole model programme was focused on double-aperture units. Four new double-aperture models and seven variants were assembled and tested. The main aim was to achieve a better understanding of the design and assembly parameters that govern the training behaviour of the coil ends. This turned out to be a point needing further attention because of the magnetic field enhancement in the coil ends of double-aperture magnets. The impact of coil pre-stress, length of the magnetic yoke, geometry and number of end spacers, and coil winding techniques could be studied in detail, providing precious feedback for the manufacture of the pre-series dipoles. One single-aperture model was also assembled and tested to ascertain the merits of a different resin for the impregnation of the coil ends.

Full-Length Prototypes and Pre-Series Dipoles

The delivery of the six full-length prototype collared coils ordered in 1998 was completed by September and the assembly at CERN of the first five dipole cold masses was completed by December 2000. The last prototype will be completed by mid-2001. In the course of the year the tests of the second, third, fourth, and fifth prototype cold masses were carried out.

All prototypes exceeded easily the nominal field of 8.3 T and reached the ultimate field of 9 T. Quenches occurred only in the coil end regions, confirming the soundness of the coil cross-section design. The last prototype comfortably exceeded the nominal field on the first quench and the ultimate field of 9 T with at most two quenches.

Concerning the manufacture of the 3 × 30 pre-series units, the three contractors made large investments to equip dedicated manufacturing halls with the necessary facilities and specialized heavy tooling.

The first units are delivered as collared coils, to be assembled into complete cold masses at CERN mainly by the contractors’ staff with the participation and guidance of experienced CERN staff as foreseen in the contracts. In this way the experience gained at CERN in the course of the prototype work is transferred to industry. In parallel the staged commissioning of heavy welding presses at the contractors’ facilities is progressing well, with some minor delay, but which is not expected to affect the delivery plan of the cold masses.

The first pre-series collared coil was delivered in October and a second one in December by one contractor; the first cold mass was completed in December. The first collared coils from the other two contractors are expected to be delivered in February 2001. Given the CERN tooling and resources, it is expected that the corresponding cold masses will be assembled by April and May 2001, respectively. Cold mass assembly is expected to start at the contractors’ premises in the first quarter of 2001.

With a view to ensuring a fast transition from pre-series to series production, CERN is equipping each of the three dipole cold mass contractors with a second complete manufacturing line for the winding, curing, and assembly of the coils. These lines are expected to be operational as from the beginning of 2002. On the other hand, 29 contracts for component procurement are at present in operation. Five other contracts are expected to be signed by June 2001.
Superconducting busbars

The manufacture of dipole cold mass busbar sets by the Budker Institute of Nuclear Physics (BINP), Novosibirsk has started and the first sets were delivered before the end of September.

An agreement for the manufacture of the busbars for the arc short straight sections was also signed with the Budker Institute.

Arc Quadrupole Magnets

Within the framework of the special contribution by France to the LHC Project, CEA-Saclay delivered the second prototype quadrupole to CERN in March. The third and last prototype will be delivered to CERN by January 2001, after full testing at Saclay. The training performance of the first two prototypes is fully satisfactory. The first had only one training quench below the nominal gradient of 223 T/m and exceeded the ultimate gradient of 241 T/m after the third quench. The second one had its first quench well above nominal gradient and exceeded the ultimate one after this first quench. The field quality of the prototypes, measured both at room temperature and in cold conditions, is satisfactory and is coherent with the mechanical and geometrical characteristics of each prototype.

The supply of 400 main superconducting quadrupoles and the assembly of the cold masses for the LHC arc short straight sections were adjudicated to a single firm for a total amount well within the budget estimates.

Apart from the austenitic steel for the collars, most of the materials and components provided by CERN will be procured within the framework of contracts established for the dipole magnets.

Magnet Quality

In the course of the year the setting-up of computer models allowing the statistical simulation of the field quality performance of dipole and quadrupole magnets was completed and validated by measurements on models and prototypes. These computer models provide the necessary means for the evaluation of magnet performance, for detecting trends, and proposing effective corrective actions in the course of series manufacture.

The field quality of the prototype dipoles was measured both at room temperature and in cold conditions. The results were coherent with the mechanical and geometrical characteristics of each prototype. They were used to propose minor modifications in some key components (yoke insert or copper wedges) required to optimize the field-shape for the series production.

Finally, the commissioning of various highly specialized devices, either procured from industry or developed at CERN for the quality inspection and control of components and completed cold masses, progressed satisfactorily. These devices will be used at the industrial premises for the contractual series inspections before delivery, and at CERN for the provisional reception tests, before the final cold test of the cryomagnets.
Measuring Equipment

A new optical instrument, developed with industry and the Ecole Polytechnique Fédérale de Lausanne (CH), was used to measure possible movements between the cryostat and the cold mass during transportation, cooling down, excitation, quench and warming up. It is based on an interferometric method and has an accuracy of a few microns. Unexpected transient deformations of up to two millimetres were observed in three prototype dipoles during the thermal transients. Sixteen optical devices were built and will be installed in three cryodipoles and one short straight section of String 2 with a view to studying cold mass deformations in more realistic conditions.

The development of the equipment for the series measurement in industry of the field-shape harmonics of the dipole cold masses at room temperature was completed. All major components for the six measuring systems to be provided to industry and the two to be used at CERN were ordered and received.

Three devices to measure the field-shape harmonics of the main quadrupoles at room temperature were built and tested. Two of them will be used to equip the manufacturers in view of series production. A third one was provided to the SL Division for magnetic measurements of the MQW warm quadrupole magnets. Courses were organized to train staff in its installation, operation, calibration, and maintenance.

A system to measure simultaneously the geometric and the magnetic axes was completed. It can be used for dipoles, quadrupoles, or high order multipoles with minor adaptations. The preliminary tests, performed both on dipole cold masses and short straight section assemblies, demonstrated that this instrument is well-suited for the final acceptance tests during series production.

A large number of search coils and integrators were built for the cold measurements of short models and full-length magnets carried out by the MTA Group.

Database Activities

The design and the implementation of the database for the data collected during the magnet procurement are continuing. A traveller will contain the data collected during component production and cold mass assembly. For each operation the traveller will contain legal paper documents and data files with results of measurement stored in Excel™ tables. A subset of these tables has been prepared; it includes filters for checking the data integrity. The traveller for cable procurement is almost complete. Forms for billet approval and strand tests have been made available and are routinely used by the cable manufacturers. The procedure for data transfer has been implemented, taking into account the severe requirements on data confidentiality.
Insertions, Correctors and Protection

LHC Insertions

The activities in 2000 were focused on further refining the system design of the insertions, as well as on the completion of the development programme of the insertion quadrupoles and launching of the series production. The layout of the LHC arcs and insertions was updated according to the optics version 6.2 of the LHC. The detailed designs of the various cryomagnet assemblies were developed and their integration with the cryogenic, powering, and civil engineering infrastructure updated.

Concerning insertion quadrupole development, a fully instrumented 1 metre long, 6 kA two-in-one insertion quadrupole with a bore of 56 mm (MQM) was completed and thoroughly tested. A 1 metre long, two-in-one 70 mm aperture quadrupole (MQY) was also fully tested. Both magnets performed particularly well, exceeding in a few quenches their ultimate current in the LHC. On the basis of these results, the technical specifications for the series quadrupoles were completed. Preparations for prototype manufacture and series production are now under way.

The collaboration with Fermilab and KEK on the design of low-β quadrupoles has progressed very well. In both laboratories the development programmes have been completed. The final model magnets performed exceptionally well, surpassing the operating current in the LHC on the first training quench at 1.9 K. Full-length prototypes are now in the final completion stage in both laboratories. Considerable advance has been made with Fermilab, KEK, and LBL in the integration of the low-β triplets and details of the interfaces. In a similar way, the collaboration with BNL, which has completed two prototypes and started building the series superconducting separation dipoles, has progressed well.

Corrector Magnets

The contracts for the procurement of all LHC corrector magnets have been placed with industry. Six new contracts were placed in 2000 for the supply of the combined chromaticity sextupoles and lattice corrector dipoles (MSCB), the tuning and correction quadrupoles (MQT/MQTL), the lattice octupoles (MO), the dispersion suppressor correction dipoles (MCBC/MCBY), and the inner triplet dipole (MCBX) and skew quadrupole correctors (MQSX). Together with the four already existing contracts of spool correctors for the main dipoles (i.e. the MCS sextupole and the MCDO octupole–decapole correctors), the total quantity of corrector magnets adds up to 2500 single-aperture and 1300 twin-aperture units. The supply of the enamelled superconducting wire for the series manufacture of the magnet coils is taking longer than expected to achieve the required quality. However, manufacture of pre-series magnets is progressing, using previously purchased wire for prototyping. The first pre-series magnets (MCS) were delivered and tested. Firms were also supplied with magnetic measurement equipment for checking field quality at room temperature and with quench detection equipment used for cold testing at the factory.

In parallel, work continued on a number of prototypes to check and finalize detailed design options as well as to ensure experimentally that the adopted quench protection schemes will safely protect the magnets in the different powering configurations encountered in the machine.
Current Leads

Measurements to qualify the behaviour of High Temperature Superconducting (HTS) prototype current leads were completed. In total, nine pairs of 13 kA and 11 assemblies, each composed of four 600 A leads, were tested. Thermal and electrical cycles were made to prove the long-term viability of HTS materials in such current lead assemblies. A number of HTS materials were tested, notably BSCCO 2223 PIT Ag-Au tapes produced by several manufacturers, as well as different BSCCO and YBCO materials in the form of bars and rods.

For installation in the String-2 test cell, seven 13 kA and twenty-eight 600 A leads, taken from the prototype production, were prepared. In the frame of the CERN–US Collaboration, 42 HTS current leads of 7.5 kA, based on the CERN development, are being produced in industry and the first pair will be tested in CERN in spring 2001. A collaboration was set up with the Kurchatov Institute (Moscow) for the study of the radiation resistance properties of different HTS materials. The design of the conduction-cooled dipole corrector leads was finalized and two assemblies of four 60 A leads were installed in two prototype short straight section assemblies.

Magnet Protection

Good progress was achieved in the fabrication and testing of pre-series equipment for quench protection and energy extraction for the different LHC magnet systems. This includes quench heaters and quench heater power supplies made by European industry, as well as the energy extraction equipment, done in collaboration with the Russian institutes IHEP (Protvino) and BINP (Novosibirsk), for the 13 kA main magnet circuits and the 600 A corrector magnet circuits. The qualification tests, as well as long-term reliability and lifetime tests, are advancing well with satisfactory results. This equipment, which is representative of the final LHC design, together with the required electronics, will be available in time for the String-2 test cell experiment. In parallel to this, the series production of the protection diodes for the main dipoles and quadrupoles as well as the cold testing of the assembled diode stacks is now well under way.

Radiation tests were performed at the SPS North Area target zone on a variety of electronic components and devices, including one heater power supply prototype, in order to guide the technical choices for compliance with the LHC radiation levels. The results are promising and the heater power supply was properly working up to 380 Gy fulfilling the LHC requirements. Simulation studies completed by the analysis of experimental data of the quench behaviour of LHC magnets allowed us to finalize the protection schemes and to define the required equipment components for all circuits of the LHC machine, including those of the corrector magnets.

A prototype superconducting busbar cable to power the insertion quadrupoles at 6 kA was developed in collaboration with IHEP (Protvino) and successfully tested at CERN. Two versions with six and $18 \times 6$ kA cables were tested. Several experimental runs carried out with these busbars as well as with the already existing $42 \times 600$ A busbars allowed us to determine their behaviour in case of a quench and to validate their design for the given applications. Other activities in this domain include the qualification of splices in superconducting busbars and cables, evaluation of methods for quality assurance of these splices and interconnects, studies of transmission line effects in the LHC powering chains, etc.
Magnetic Field Calculations

The field computation section (MF) provides CERN-wide support for magnetic field computations and magnet optimization using the CERN-ROXIE program package. The program package was upgraded for the calculation of superconducting filament magnetization, solenoids, and permanent magnet materials. A new parametric mesh generator for higher-order quadrilateral finite elements was developed at CERN and combined with the BEM–FEM method that couples the finite-element technique (inside the iron yoke) with the boundary-element technique in the air region. This implies that the air regions do not need meshing and that artificial far-field boundaries can be avoided. Based on this method, a model for the superconducting filament magnetization was implemented, which allows the calculation of hysteresis effects in superconducting magnets and the taking into consideration of local saturation effects in iron domains. Another activity of the section is the development of approximation schemes for the objective function formulation in mathematical optimizations of magnet designs.

On the design and evaluation side, the section was involved in finalizing the main dipole cold mass geometry and in setting up a database of computational models for all corrector and insertion magnets.

Magnet Test and Analysis

As in the past, intensive test programmes with tight schedules were pursued in both the MTA test plants, one in ‘Block 4’ (Bldg. 892) for the short model magnets and the other in SM18 (Bldg. 2173) for the LHC dipoles and short straight sections.

While the number of tests of short model dipoles (12 test runs) remained about the same as in 1999, the test sequence for corrector magnets, diodes and model quadrupoles increased, as expected from the overall evolution of the LHC programme. In parallel, the CERN-built test benches for the warm measurements of the MCS and MCD corrector magnets were commissioned. They were shipped to the manufacturers of these magnets in Spain (ANTEC) and to the CAT laboratory (India) where they are now being operated to qualify the first series magnets.

Preparations are in progress to test the first LHC quadrupoles in a newly designed vertical cryostat, before cryostating, allowing for an early assessment of the performance and the field quality in 2001.

In SM18 two test benches were fully commissioned together with the prototype supply boxes (CFUs). In total four prototype dipoles and two short straight sections underwent extensive tests, each including several thermal cycles. These tests provided valuable feedback and input allowing the magnet design to be finalized as well as the test equipment and procedures to be used during series tests. In particular, for the cold measurements of the quadrupoles, a newly developed and unique system was commissioned which allowed us to measure simultaneously and with high precision the field, harmonics, direction, and the centre of a quadrupole. A large amount of data were acquired allowing for a detailed assessment of the performance of these quadrupoles.

The test teams, already working partially in shifts, were supported by operators from India within the framework of the LHC–India Collaboration. This support is expected to increase in the coming year during the
pre-series and the series phase when six operators will be at CERN at any time. In parallel, a contract with European industry is being prepared to provide the remainder of the work force to man the test teams, working around the clock during the series phase.

An in-depth review with international participation from Germany, Japan and the USA was held to verify the test programmes, the procedures and the means for the series tests. This greatly helped to clarify the subject and define clearly the strategy and procedures. As a result, twelve test benches were recommended to cope with the delivery schedule of the series magnets. The recommendations from this review are now being implemented and market surveys and price inquiries for the required hardware are being launched to be ready and fully operational for the series measurements as of the year 2003.

**Cryostats and Ring Integration**

The year 2000 has seen the finalization of the design and of the specification of most of the standard arc components, assemblies and subassemblies, and the launching of most of the large market surveys and invitations to tender. Up to 70% of the standard arc cryostat systems were contracted or adjudicated in European industry in 2000, representing a total amount of 97 MCHF.

This concerns the contract for the 1250 dipole vacuum vessels, under which the first 50 series vessels should be delivered in 2001. Eight pre-series vacuum vessels were delivered under a separate contract, of which five have been used to assemble the last five dipole prototypes. The 1250 dipole thermal shield contract was attributed, and the first series assembly delivered. The contract for the 360 standard short straight sections was signed, and the organization work started.

In addition, large adjudications of components done in 2000 concern the cold support posts for the arc cryomagnets (~5000 units), the 150 arc cryostat insulation vacuum barriers, the dipole multilayer superinsulation blankets (1250 sets), and the interconnection bellows between arc cryomagnets (more than 19 000 bellows with diameters ranging from 80 mm to 1100 mm).

In preparation for the series assembly production and testing of the LHC cryomagnets, a market survey to European industry was made and the specification was written for the supply contract of the work packages ranging from cryodipole and special SSS assembly, preparation for tests and connection to the test benches of all cryomagnets, up to the final preparation for assembly in the tunnel.

The new SMA 18 building, funded by the Conseil Général de l’Ain within the framework of the special contribution of France to the project, was completed and its infrastructure is being set up to host the assembly and preparation of the series cryomagnets. Following an invitation to tender, the adjudication of the five heavy cryostating toolings to be installed in this hall in 2002 is being prepared. A number of invitations to tender for orbital welding and cutting machines, rolling and bending machines, and transport and handling equipment required for these work packages were launched. The first special handling vehicle for cryomagnets was received at CERN.
Concerning design, the Instrumentation Feedthrough Systems for arc cryomagnets (IFS) was completed and validated by cryogenic and electrical type tests. A market survey was launched for the procurement of the 1730 such systems required for the machine.

In the framework of the collaboration with CNRS-IN2P3, France, the design of the short straight sections (arc) was completed. The second prototype Short Straight Section (SSS) was successfully assembled at CERN in the beginning of the year, and is now integrated in String 2, while the first prototype has undergone a second campaign of measurements before its preparation for String 2. Both prototypes have successfully confirmed the SSS design, the assembly procedure and tooling retained, and shown the expected performances. The procurement of the parts necessary for the assembly of the third prototype (SSS3) early in 2001 has been done. In parallel, the conceptual design of the arc dispersion suppressors special SSS was completed and the procurement of the cryostat components integrated in the contract of the SSS Arc. Connection cryostats, the last missing machine component of the LHC dispersion suppressors filling the gap of about 12 m between the SSS in Q11 and the neighbouring cryodipoles, were conceptionally designed and will be presented in a Dispersion Suppressor Design Review in January 2001.

The design of the String 2 electrical feedbox was finalized, and the components manufactured and delivered to CERN for assembly as an addendum to the CERN–BINP collaboration agreement. Superconducting busbars were delivered by industry, and the assembly work at CERN started.

Following the adoption of the new optics version 6.2, additional layout studies for arc electrical systems were conducted. This has allowed a final optimization of the architecture of the arc electrical feedboxes (DFBA), a significant reduction in the number of current leads and of superconducting electrical cables to be routed inside the cryostat, and a consequent reduction of the number of electrical interconnections between cryomagnets. Conceptual studies of the final machine DFBAAs were started in collaboration with BINP under a separate ad hoc addendum to the agreement. A conceptual design review is planned in March 2001, followed by a detailed design in collaboration with BINP.

The collaboration with CAT (India) for the development and manufacture of cryostat positioning jacks entered its production phase. A pre-series of 36 pieces made in India, to be used in String 2, was commissioned at CERN.

The technologies and procedures to perform the interconnections of the LHC cryomagnets were further developed and optimized. A design review of the LHC arc interconnections was organized in April 2000. The engineering file of the dipole–dipole interconnection was sent for final approval in December. The next standard interconnection files will be sent for approval at the beginning of 2001.

The components necessary for String 2 interconnections were defined and ordered. The drawings of the String 2 interconnections were finalized. The first interconnection between a short straight section and a dipole of String 2 was performed at the end of the year. The next ones will follow at the beginning of 2001.

The technologies were validated on a full-scale interconnection model and during the first interconnection of String 2. Inductive soldering and ultrasonic welding developed by the CERN–CNRS (LAPP) collaboration were successfully applied. The design of the thermal shield and of the support of the radiative insulation was finalized and tested on a full-scale mock-up.
Activities to be performed in surface buildings (SM18, SMA18, SMI2) to prepare cryomagnets (dipoles and SSS) for cold test and later on for installation in the LHC main ring were defined.

The definition of control and quality assurance activities was also started for all the tasks related to the interconnections.

Transport studies of the cryomagnets in the tunnel were pursued; these led to the specification of the tunnel transport vehicles, submitted to European industry.

Finally, integration studies of the machine components in the tunnel were continued, with a view to preparing the future installation.

**Vacuum**

**PS Complex**

The group continued to provide the required support for the vacuum systems of the accelerators including ISOLDE. The nTOF beam line vacuum was successfully installed and commissioned during the year. The group provides continual support for the CTF programme and for LHC-related upgrades of the vacuum systems. The reduction of impedance by eliminating harmful discontinuities in the vacuum flanges of the PSB rings was completed. As part of the design of the future LEIR ring, an experiment to measure the ion-induced desorption rate by heavy ions was installed and gave the first results shortly before the annual shutdown.

**SPS**

The improvement programme with the replacement of the 1200 high-voltage power supplies for ion pumps is progressing on schedule. A significant effort was made to minimize the doses that maintenance personnel receive during interventions by optimizing the procedures and layouts.

The installation of RF-shields in the pumping ports of the SPS vacuum system to reduce the transverse impedance was completed for one-sixth of the SPS. The remaining pumping ports will be equipped during the 2000/2001 shutdown by the industrial support team under a result-oriented contract. In addition the group provided support for the vacuum of the CNGS line.

Studies with LHC-type beams and high bunch intensities continued, in order to measure the effect of beam-induced multipactoring in the vacuum system. The existence of a threshold in the beam intensity required to trigger the phenomena could clearly be demonstrated.

**LEP**

The operation of the LEP vacuum system at the record beam energy and beam currents remained a unique challenge for the whole group. Thanks to a thorough maintenance plan, perturbations linked with the
degradation of the equipment due to radiation could be minimized. Any intervention had to be very carefully planned in order to avoid damaging the cables that had become very brittle because of radiation.

Last but not least, the group participated intensively in the preparations for the swift dismantling of the vacuum system and it is planned that maximum use of LEP vacuum components will be made for the LHC. A database was created together with the responsible persons from SL Division to satisfy the traceability required by the French INB regulations.

LHC Project

Vacuum components for the two SPS-to-LHC beam transfer lines are being built at BINP Novosibirsk and the first chambers have arrived at CERN and were successfully tested.

The design of the beam screen for the main ring vacuum system was finalized. Insertion tests of a beam screen into the cold bore showed that bronze-coated sliding rings are required in order to limit the required force and to avoid damage on both the screen and the cold bore. The validation of this concept in terms of heat load to the 1.9 K cold bore was completed in collaboration with the ECR group. The final specifications and the call for tender for the series production were issued and a contract was awarded in December 2000.

A major redesign of the interconnect assembly of the vacuum beam vacuum lines between cryostats led to a significant simplification, reviewed and approved in spring 2000. A collaboration agreement was signed with BINP at Novosibirsk for the fabrication of most of the components for the interconnects. The first prototypes will be available for installation into String 2.

All equipment required for String 2 has been manufactured and is ready for assembly. Deformation tests of the beam screen during a quench were made, demonstrating that the beam screen is not only deformed by the strong eddy currents, but is also pushed towards the cold bore. String 2 will be equipped with measurement devices in order to verify the various hypotheses leading to this displacement.

The design of the vacuum system for the long straight sections according to the version 6.2 optics is being studied in collaboration with other groups concerned. The search for a cryosorbing material that will be required for the part of LHC where the cold bore is at 4.5 K is ongoing. Significant progress was made in the definition of the vacuum instrumentation required for the beam and insulation vacua of the arcs. Prototype mobile pumping stations that can be fitted below the cryostat have been built. A test programme was launched in collaboration with the University of Magdeburg in order to define a reliable operating mode for the gauges used in the insulation vacuum.

The engineering design review of the TAS/TAN absorbers adjacent to the experiments took place, leading to a significant change in the proposed vacuum chamber of the TAN. For the vacuum chambers for the experiments, a review validated the design of the ATLAS and CMS vacuum systems and the major development projects for the experimental vacuum systems are close to completion. A full-scale 40 m prototype of the ATLAS vacuum chamber was assembled and will be used to make tests with the sputter-deposited Non-Evaporable Getter (NEG) films developed at CERN. Damping measurements with various materials that could be used for the supports of the experimental vacuum chambers are ongoing.
Measurements were continued to study the non fully understood dose dependence of the secondary electron yield. The influence of the residual gas composition was investigated and it was found that a large change in the partial pressure of carbon-containing gases (e.g. CO and CH₄) does not influence the rate of decrease of the secondary electron yield. In parallel, a measuring system was prepared for the remote measurement of the secondary electron yield in the SPS accelerator. This system will be installed during the 2000/2001 shutdown.

Towards the end of 1999 the COLDEX cryostat was installed for the first time in the EPA ring and the vacuum performance of a cryogenic vacuum system in the presence of circulating electrons or positrons was studied. In 2000 COLDEX was re-installed on the external beam line and gas desorption studies of co-laminate copper with saw-tooth structure were performed. Throughout this period, the effect of photon and electron scrubbing on the secondary electron yield of copper was measured on another external photon beam line under conditions closely simulating the LHC. These measurements provide valuable input for the expected pressures in LHC and are used to check the predictive power of simulation.

Collaborations with other institutes include gas desorption measurements which were made on proposed liners (passively cooled beam screens) for the LHC inner triplets on the VEPP2 machine at BINP, Novosibirsk. Measurements are ongoing at the same institute to study the dynamic vacuum performance of sputter-deposited NEG films developed at CERN. A closed-cycle cryostat/manipulator system was commissioned at CERN, in collaboration with INFN, for measurements of electron emission from surfaces at cryogenic temperatures.

**Industrial Automation and Supervision**

The compressor station for the 18 kW cryoplant in P1.8 was successfully put into operation with the latest ABB equipment. The unified project for cryogenics controls of the LHC machine and experiment magnets was tendered and awarded and the design work by the selected firm has started.

A collaboration in the domain of supervision was set up with India within the general cooperation agreement. The first versions of the programs for the supervision of String 2 have been commissioned successfully.

The supervision system for the ATLAS barrel toroid prototype B0 was installed for the initial tests on a small-scale model B00.

The control equipment for six magnetic measurement systems and three quench recording systems to test corrector magnets in industry were delivered. A first version of the Test Master program that will orchestrate the test benches was commissioned. A preliminary version of a program for automated geometric measurements of LHC dipoles, using Leica Geosystems equipment, was delivered. The control equipment for the Strand Magnetization Measurement system in Bldg. 163 was fully commissioned.

Both the industrial Profibus DP and WorldFip interfaces were qualified in a radioactive environment up to 950 Gy. The possibility of synchronizing LHC equipment with a resolution of 10 µs using the industrial
WorldFip fieldbus was demonstrated. The transmission of date and time with a resolution of 1 ms also proved to be possible, using the same industrial fieldbus.