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The LHC Prototype Full-Cell: Design Study

F.Bordry, JC.Brunet, J.Casas-Cubillos, P.Cruikshank, K.Dahlerup-Petersen, N.Delruelle, D.Hagedorn, J.Kragh, R.Lauckner, J.Pett, P.Proudlock, G.Riddone, F.Rodriguez-Mateos, P.Rohmig, R.Saban, L.Serio, C.Wyss

Abstract

As a continuation of the experimental program carried-out with String 1, project management decided towards the end of 1995 to construct an LHC prototype Full-Cell, also known as String 2. The present document reports on the outcome of the one-year design effort (see Annex 1) by the community of specialists contributing to the LHC Prototype Full-Cell: it informs specialists on the boundary areas with other systems and conveys to the general public a description of the facility.

LHC and SL Divisions

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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Edited by R.Saban with contributions from F.Bordry, JC.Brunet, J.Casas-Cubillos, P.Cruikshank, K.Dahlerup-Petersen, N.Delruelle, D.Hagedorn, J.Kragh, R.Lauckner, J.Pett, P.Proudlock, G.Riddone, F.Rodriguez-Mateos, P.Rohmig, R.Saban, L.Serio, C.Wyss.

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Summary

As a continuation of the experimental program carried-out with String 1, project management decided towards the end of 1995 to construct an LHC prototype Full-Cell, also known as String 2. The present document reports on the outcome of the one-year design effort (see Annex 1) by the community of specialists contributing to the LHC Prototype Full-Cell: it informs specialists on the boundary areas with other systems and conveys to the general public a description of the facility.

Objectives

The LHC Prototype Full-Cell constitutes the last opportunity, before installation in the tunnel, to validate individually the LHC systems and to investigate their collective behaviour in normal and exceptional conditions as well as during transients. Therefore during the design, the guideline of installing the systems in their final or close to final version has been adopted. This has resulted in an experimental facility which will be as close as it can be to a full-cell situated in the regular part of the arc, assembled five years in advance of the collider.

String 1, the predecessor of the LHC Prototype Full-Cell, has yielded large amounts of data and precious information. This information is however limited by the version of the components (eg 10-m long dipoles, prototype quench relief valves) available at the time of construction and to its configuration (eg. cryogenic lines traversing the magnet cryostats, half-cell). For the first time, experiments at the LHC Prototype Full-Cell will offer the possibility of investigating final design choices for key components and on a larger scale.

The performance of the cryogenic system with the separate line and its connection every cell to the collider will be measured for the first time with real loads, with the new cylindrical bayonet heat exchanger and in a portion of the machine which is installed in a horizontal plane. The thermo-hydraulics of quenches with the new design and configuration (two per cell) of the quench relief valves will be observed.

The presence, for the first time, of several independently powered electrical circuits will allow the investigation of their mutual influence during normal operation and in case of quench. Furthermore, techniques for tracking the main dipole magnets as well as their correctors during transients will be studied. The final design of the tube external to the magnet cold mass routing the auxiliary bus-bars will be tested in real operating conditions and installation aspects of the cables inside the tube will be verified.

Operational experience will be gained with a prototype of the d.c. breaker facility which is foreseen for the LHC machine.

The final design of the magnet protection system with individual magnet quench detection and heater control will be validated.

Results of dipole to dipole quench propagation experiments performed with String 1 will be verified with the different and final dipole-to-dipole mechanical and hydraulic interface as well as with the larger inductance of the final coils. Quench propagation from main magnet to corrector, dipole to quadrupole, central dipole to neighbouring dipoles and half-cell to half-cell will be studied for the first time.

Experiment with vacuum barriers present within the separate cryogenic line, in the magnet string and between the string and the cryogenic line will be carried-out. The cooling of the beam screens installed in each half-cell and independently controlled will be studied and validated.

Last but not least, the LHC Prototype Full-Cell will offer a unique occasion to rehearse the assembly and exchange sequences and to verify the assembly procedures foreseen for each step of the interconnection of magnets as well as the exchange of a diode or instrumentation. Transport and installation equipment designed to operate in the tunnel will be tested for the first time in the real operating environment.

In addition to these studies which will all be carried-out for the first time, a number of experiments, measurements or exercises which already took place with String 1 will be repeated either to confirm the results obtained or to test newly developed versions of an already verified/tested component. These include

- for cryogenics, the measurement of the overall performance of the system (cool-down and warm-up times, temperature stability during steady state and transient operation, heat loads) and the verification of the advanced control techniques for the superfluid helium loop,
- for vacuum, the evaluation of the final instrumentation.

In addition to the results expected from the experiments, String 2 will provide the future operations crews with valuable experience in the fields related to running a superconducting collider.

Schedule

The assembly of String 2 will extend from the second half of 1999 to the first half of 2000 (see Annex 2). The commissioning of String 2 is foreseen for June of the year 2000. Experimental runs are scheduled until the human resources are redeployed for preparation of LHC commissioning; these runs are interspersed with shutdowns, when modifications or upgrades are carried-out.

Conclusions

Following the identification of the areas to investigate with the facility, the design of String 2 has progressed to a point where all the requirements for the component systems have been stated. Altough for some of the systems some prototyping effort is still required, the design, the technical specifications for tendering and, in some cases, the manufacturing of most of the components have already started.

The construction schedule of the facility has been adjusted to be early enough to allow experimental results to still influence the design of the final components, but late enough to permit to test close-to-final versions of each component.

The sections that follow describe the layout and the component systems of the facility.

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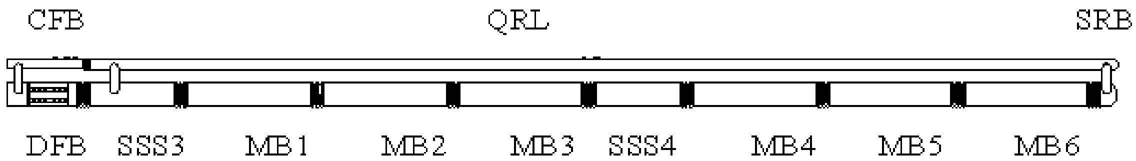
1 Layout and Main Components

The LHC Prototype Full-Cell, also called String 2, has the same layout of an LHC cell situated in the regular part of an arc (See Annex 3) and also follows the curvature of the tunnel. It is situated in bay 4 of building 2173 (SM18). With its 114 meters, it covers almost the whole length of the building (120 m).

String 2 is composed of two half-cells. The first half-cell starts with a short straight section (SSS3), which is connected to the cryogenic line (QRL) via a jumper connection and is followed by three 15-m dipoles. The second half-cell starts with SSS4 that is not connected to the QRL and is followed by a second set of three 15-m dipoles.

The first half-cell is preceded by an electrical feed box (DFB) which supplies the current to the 15 electrical circuits of String 2. A String Return Box (SRB), which is connected to the QRL, ends the string of magnets.



2 Magnets

2.1 *The Short Straight Sections*

As their main magnetic component the Short Straight Sections (SSS) contain a 3.10 m. twin aperture quadrupole. It generates a gradient of 223 T/m at 11870 A.

The super-conducting cable of the quadrupole magnets will be the same as the key-stoned cable used for the outer coil layer in the main dipole magnets.

Each short straight section will have on the end opposite to the connections, the sextupole-dipole corrector magnets. The sextupole coils of these combined units will be powered in series to currents up to 500 A nominal. The corrector dipole magnets, alternatively either horizontally or vertically deflecting, will be powered individually. This means that their current feeding between 1.9 K and room temperature is required in every short straight section. Their maximum operational current will be 32 A. The yoke length of these units will be 1.26 m. The sextupole strength is 1500 T/m^2 over a magnetic length of 1.10 m. The corrector dipole field is 1.5 T over 1.03 m. These coils will be assembled in a common yoke and fixed inside the inertia tube similar by to the main quadrupoles.

On the connection side of the quadrupole two octupole corrector magnets of 380 mm overall length will be mounted. Their strength will be $6.7 \cdot 10^4$ T/m^3 over a magnetic length of 320 mm. Their outer diameter will not be more than 117 mm and thus they will be mounted separately and fixed by a pair of plates inside the inertia tube. The nominal current will be 600 A.

The technical service module of the SSS is placed on the connection side of the magnets. This module contains the beam position monitors, the protection diodes for the quadrupole magnets and the cold mass instrumentation capillaries. In the first SSS, the technical service module contains the jumper connection to the separate cryogenic line and the helium phase separator.

2.1.1 SSS for the first half-cell (SSS3[1])

SSS3 includes the quadrupole with its diodes and lattice correctors, a fully equipped beam position monitor, a standard beam vacuum pumping port and a cryo-cooled beam screen in each beam tube. A vacuum barrier for the longitudinal subdivision of the insulation vacuum of the magnet cryostat chain is also mounted in this SSS. Furthermore, bus-bar plugs, which hydraulically separate every two cells in LHC, are also mounted. This particular configuration, DFB followed by a SSS with bus-bar plugs, will never be present in the collider; however, the assembly of the most complex SSS and its test justifies this deviation. However, in order to allow the testing in nominal operating conditions (end box of DFB hydraulically connected to the HeII bath of the arc) of the DFB, the bus-bar plugs are by passed in the DFB-QQS interconnect.

The technical service module (QQS) of SSS3 is similar to the one in the SSS of half-cell 27 of an arc situated at the left-hand side of an insertion. It is on one side interfaced to the electrical feed box (DFB) and on the other one to the QRL via a standard jumper connection. This jumper connection, which is of type B, provides the supplies and most of the returns of the cryogens servicing a standard cell. Annex 4 shows the SSS3 assembly.

The magnetic components of SSS3 are MQF/D, MO and MSCBH/V.

2.1.2 SSS for the second half-cell (SSS4)

Following the simplified cryogenic scheme, SSS4 is not connected to the QRL. It is similar to the one in the SSS of half-cell 26 of an arc situated at the left-hand side of an insertion. It includes the quadrupole with its diodes and lattice correctors, a fully equipped beam position monitor, a standard beam vacuum pumping port and a cryo-cooled beam screen in each beam tube.

The magnetic components of SSS4 are MQD/F, MO and MSCV/H.

2.2 The Dipoles

It is planned to equip String 2 with six 15-m long dipoles prototypes of the second generation, featuring a 6-block coil cross-section and aluminium collars without magnetic inserts. The coil cross-section, as defined at the price inquiry stage, is shown in Annex 5 (Drawing LHCMBPA_0013). The inner and outer coil layers are separated by an interlayer spacer providing helium distribution channels also between the collaring shim and the turn of the inner layer next to it.

For scheduling reasons (availability of the fine blanking tooling), the first two dipole magnets will be assembled with collars and yoke laminations not fully optimised for field quality and will have an interbeam distance of 194 mm at 300 K. The following four dipole magnets will feature fully optimised collars and yoke laminations with an interbeam distance of 194 mm at 1.8 K.

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[1] This numbering reflects the order of manufacturing of the quadrupole cold masses. SSS1 was mounted on String 1 and the second quadrupole, which was tested in Saclay, was never assembled in a SSS.

The dipole cold masses weight about 25 t and are curved with the nominal bending radius of 2804 m, corresponding to a sagitta of about 10 mm, between endplates.

The nominal filling factor of the yoke lamination packs is 98%. The cylindrical bayonet He II heat exchanger will be of the smooth-wall type, made out of a 1/4-hard copper tube with brazed-on austenitic-steel ends, one end being equipped with a bellows.

The cold-bore tubes (53/50 mm) in these magnets will be welded directly to the endcaps without bellows.

The six dipole magnets will be equipped with so-called flux-loop coils to measure the main field. These coils consist of 0.5mm wide, 0.018 mm thick Cu tracks deposited on a 0.125 mm thick polyimide foil, which is then placed around the cold bore tube.

The quench heaters equipping the prototype dipoles will be of the type foreseen for series production, see section 4.7.

The prototype dipole and quadrupole bus-bars have a Cu stabilising cross-section of about 260 mm^2 and 160 mm^2, respectively. The dipole bus-bars are in addition provided with a hole of 5 mm diameter, to keep a sufficient mass of He II in close contact with the stabilising copper. Should it be experimentally proven that this hole is not necessary to stop quench propagation, it will be suppressed.

The collared coils will be produced by industry (three firms producing two assemblies each). The assembly of the first collared coils from each firm into cold masses will be carried out at the Magnet Assembly Facility at CERN, whereas the assembly of the remaining cold mass will be entrusted as much as possible to the firms themselves. As in the past, all cold mass major components will be procured by CERN.

2.3 The Magnet Interconnects

All three types (MB-MB, SSS-MB, MB-SSS) of interconnects are present on String 2 (see drawings in Annex 6). The interconnects will implement all the functions foreseen for LHC. The dimensions of the cryomagnets follow rigorously the final design values[2].

The installation and the interconnection (soldering, welding) procedures will be those foreseen for LHC. Each operation will be accompanied by a quality insurance protocol and executed by certified welders.

The external routing of a multi-strand superconducting cable feeding the SSS correctors (octupoles, sextupoles) will be implemented. Electrical connections (connectors) will be done in accordance with the final machine design choices.

3 Cryogenics

The cryogenic system is based on the Yellow Book updated by the report on the *Simplification of the Cryogenic Scheme (LHC Project Note 106)*. It is designed to allow all transient modes (cool-down, warm-up, current ramping/de-ramping and quenches) as well as steady-state operation of String 2. The system comprises the cryoplant, a Cryogenic Feed Box (CFB), the Cryogenic Distribution Line (QRL), the Electrical Feed Box (DFB), the cryogenic piping and modules inside the magnet string and the ancillary systems.

[2] See LHC Project Note 50

String 2 is installed on a horizontal plane in order to investigate the behaviour of the superfluid helium loop in the worst configuration with respect to the thermohydraulic phenomena. Other slope configurations have already been tested with String 1 and are currently under investigation at a dedicated test loop in Grenoble.

3.1 The Cryogenic Flow-scheme

The Cryogenic Flow-scheme is given in Annex 7. Two separate and thermally shielded transfer lines connect the 6 kW refrigerator to the String via the Cryogenic Feed Box.

During normal operation, three loops are fed by the Cryogenic Feed Box and extend over the whole of the string:

1. Line E feeds the thermal shields and heat interception at 50 K and returns via the QRL thermal screen line,
2. Line C feeds two separate loops with supercritical helium (3 bar, 4.5K) :
   a) the bayonet heat exchanger in the cold mass via the very low pressure heat exchanger. The expansion of the supercritical helium in the Joule-Thomson valves provides cooling of the pressurised superfluid helium inside the cold mass. Superfluid helium is fed to the far end of the string via the heat exchanger inner tube. Line B provides the pumping to the saturation pressure of the superfluid helium loop.
   b) the heat intercept at 4.5 K and the beam screens. Line D recovers the return gas.

Line C is also used for cool-down and warm-up of the cold mass with a forced flow of gaseous helium and to fill the cold mass with the liquid helium. Gaseous helium is recovered in line D.

After a resistive transition, the helium expelled from the cold mass via the Quench Relief Valves at each end of the string into line D, is buffered through the Quench Buffer Vessel and transported to the low pressure recovery and the Warm Buffer.

The DFB is fed with 4.5 K liquid helium and 20 K gaseous helium. The bottom part of the high critical temperature superconductor (HT_cS) current leads are immersed in a 4.5 K liquid helium bath supplied by line C via a Joule-Thomson valve. The 20 K gaseous helium cools the classical part of the current leads from the return of line D. Warm gas recovered from the DFB is sent directly to the warm recovery line of the refrigerator.

3.2 The Cryogenic plant

An existing 6 kW helium refrigerator manufactured by Linde will be re-used for String 2. In order to supply the large liquefaction capacity required and to reduce the cool-down time, the 6 kW cold box has to be boosted by the addition of a liquid nitrogen (LN_2) precooler unit.

The total equivalent entropy flux with HT_cS current leads is 347.4 $J.s^{-1}.K^{-1}$. This corresponds to a refrigerator with an equivalent cooling capacity of about 1.6 kW at 4.5 K (see Annex 8).

Although the 6 kW refrigerator would be sufficient to ensure the steady-state operation of String 2, the LN_2 precooler becomes necessary in order to reduce the cool-down time from 300 K to 90 K of the 160 t of low-carbon steel and aluminium used in String 2.

The 6 kW refrigerator and String 2 will be cooled-down and warmed-up together. Four operating modes are thus foreseen: a cool-down phase from 300 K to 90 K, a second cool-down phase from 90 K to 4.5 K, a third phase corresponding to steady-state at 4.5 K, and finally, a fourth phase for the warm-up from 4.5 K to 300 K.

The synoptic diagram of the 6 kW refrigerator cold box, the LN_2 precooler and the string of magnet is given in Annex 8.

3.3 The Cryogenic Feed Box

The Cryogenic Feed Box is an interconnection module between the transfer lines coming from the refrigerator and the Cryogenic Distribution Line (QRL). It contains a minimum of instrumentation and valves to distribute helium in the various circuits and retrieve the exhausted gases back to the refrigerator or pumping group depending on their temperature and pressure.

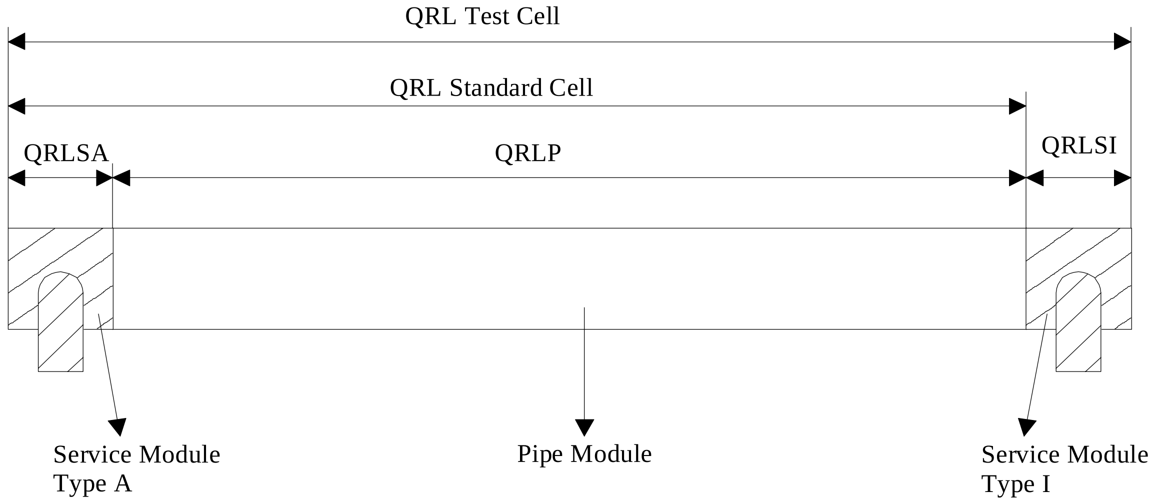
It also includes a jumper connection to provide and recover helium at 4.5 and 20 K to the Electrical Feed Box as well as the thermal-screen cooling loop which is fed into the string of magnets via the CFB and the DFB.

3.4 The String Return Box

The main functions of this unit are to provide the second quench relief valve for String 2 (line D), the connections for the beam screen cooling (lines C and C') for the second half-cell and the return of line F to the separate cryogenic line. Installed just after MB6, it terminates the string of magnets and is connected to the QRL via a type I jumper connection.

3.5 The Cryogenic Distribution Line

The Cryogenic Distribution Line that feeds String 2 is the *QRL Test Cell* which will be tested extensively by December 1999. These tests include the investigation of heat inleaks, thermal cycles and pressure tests. The naming convention used for identifying all the QRL sub-assemblies is shown in the figure below.



In the LHC, the QRL standard Arc comprises 23 *standard cells* (106.9 m) each of them consists of one *service module* and one *pipe module*. The QRL Test Cell consists of a service module of type A, straight pipe elements of transportable length with the inner and outer bellows systems and a service module of type I. The main parameters of the QRL headers together with a layout of the QRL Test Cell are given in the Annex 9.

In order to follow the LHC curvature, the QRL Test Cell will have the same polygonal shape as needed later in the tunnel. As a consequence the QRL inner and outer displacement compensation must be able to take a total angle of ~0.6°. The installation, alignment, assembling and leak testing procedures of the QRL Test Cell will follow the same procedure envisaged for the QRL in the tunnel.

The approximate total length of the QRL Test Cell is 110 m and the vacuum jacket outer diameter is 610 mm.

The service module type A houses the interconnecting pipes and valves (see Table 3 in Annex 9) needed for the magnet string cool down, for the beam-screen cooling loop and for the 1.9 K circuit. With respect to the LHC machine, only one beam screen supply will be used for String 2.

The Service Module type I (see Table 4 in Annex 9) is used for returning the gaseous helium during cool-down and for the beam screen cooling loop.

3.6 The Ancillary systems

The ancillary systems include the Quench Buffer Vessel, the Warm Buffer Vessel, the pumping group and all interconnecting piping and valves.

The Quench Buffer Vessel acts as a liquid helium decanter. It replaces part of the buffer volume that would be available in the 3.3 km-long line D of a sector. Liquid helium and gaseous helium expelled after a quench from the magnets will be separated here and the gas will be discharged via a long external line, acting as a natural heater, in the Warm Buffer Vessel capable of containing almost all the helium inventory of the string (20 bar, 80 m^3).

The pumping group provides 16-mbar pumping for the superfluid helium loop. It consists of a Cold Compressor and the Warm pumping group. It will be shared among other users in SM18 but it can provide up to 18 g/s pumping capacity at 16 mbar. It will be connected to the Cryogenic Feed Box via a thermally screened line to keep the gas at the inlet of the Cold Compressor below 5 K.

During cool-down, the warm gas will be pumped first to the refrigerator before switching to the Cold Compressor once they are at 5 K.

3.7 Instrumentation

String 2 will be used to investigate the long term behaviour in operation of various types of sensors, the ease with which they can be interfaced to control and diagnostics equipment and their maintenance requirements. Therefore, an effort has been made to install on String 2 instrumentation that is as close as possible to the one that will be installed in LHC: a preliminary description of this instrumentation is given in the Yellow Book. At present much effort is devoted to the study of cryogenic thermometers, cryogenic pressure sensors, cryogenic flow meters and in general *radiation tolerant* instrumentation to be installed inside the LHC tunnel.

4 Powering and Magnet Protection

String 2 will be equipped with a full set of corrector magnets and the main quadrupole circuits will be separated from the dipoles. This was not the case for String 1. This will allow the validation of the overall powering configuration and in particular the bus-bar dimensions and routings as well as the interconnection procedures during installation. The Power Converters will be the same as those proposed for the machine and will include the regulation and control philosophy that will be used in the machine.

In order to balance the inductance of the main dipoles between the go and return busbars in the LHC machine, the dipoles are connected in alternate ½ cells to either the go or return busbar. This will also be done in String 2 and will therefore require three magnets of each connection type. Likewise, String 2 will need one FD quadrupole and one DF quadrupole to satisfy the full cell requirements.

4.1 The Electrical Circuits

The electrical circuit diagram for String 2 is shown in Annex 10. It reflects the powering configuration of the machine as so far as it is possible with one cell of the machine. The six main dipoles and their correctors (total of 24 connected in four families) are split between the go and return bus-bars so as to balance the inductance. A third bus-bar is used for each family of dipole magnet correctors connected to the centre point of the circuit. This is foreseen to allow the immediate powering of half the corrector circuits in case of a corrector failure and later it can be used to bypass the faulty magnet during a "short intervention". It also provides a convenient measuring point for quench detection purposes.

The two main quadrupoles are powered separately for each aperture to form one focusing and one defocusing circuit. The eight correctors of the short straight sections are connected individually to the electrical feed box that will allow any combination of connection to be made on the warm side.

4.2 Power Converters

The main dipoles will be powered in series by the existing 2-quadrant converter of String 1. This converter [20kA, ±14V] is a conventional 12-pulse thyristor converter, made up of four 5000A modules connected in parallel.

To power the main quadrupoles, two new switch-mode power converters will be installed. These converters will also be made up using a modular concept, where several high-current sources [3.25kA, 16V] are placed in parallel.

This concept provides operational redundancy, since 5 modules will be installed for each converter. These modules (50 kW) will use soft-switching technology, working at a frequency greater than 20 kHz. Each module will employ water-cooled and plug-in sub-assemblies, thus improving availability and repair time (fast exchange and off-line repair).

A third high-current low voltage switch-mode power converter will be installed to test the definitive topology to be used for the main LHC dipole converters, namely a SCR booster converter [13kA, ±180V] for the ramp up and the ramp down, in parallel (or in series), with a low voltage 1-quadrant switch-mode power converter [13kA, 16V].

All the corrector magnets will be fed by 4-quadrant switch-mode power converters (±600A and ±60A). New designs are under development to improve the efficiency and volume of these converters.

For the power converters and their control, String 2 will be an important place to test and validate all the new concepts needed in the LHC machine. The requirement to track the dipole converters and the reference magnet converter currents to 5 ppm, places new constraints on permissible error in many areas. Equally, the techniques for on-line correction need such new methods to be fully evaluated before series production of control electronics can be envisaged.

The main areas which will be evaluated include all the power related aspects mentioned above, the current measurement systems including their calibration methods and instrumentation, digital regulation loops, reference waveform generation with on-line corrections and methods for data transmission and machine timing. Many of these areas will be developed using the magnet test benches, but String 2 is a full-scale model for test.

4.3 The Electrical Feed Box (DFB)

The DFB provides a thermal transition between an electric current source operating at 300 K and a string of cryomagnets operating at 1.9 K. The DFB is, on one hand connected to the cryogenic line for the supply and return of cryogens and, on the other hand to the SSS of the first half-cell. Three 13 kA circuits and twelve 600A circuits (See Annex 10) traverse the DFB to supply the main magnets and their correctors.

The water-cooled cables at room temperature are connected to the warm end of the current leads. As for LHC, the String 2 DFB is equipped with high temperature superconducting (HT_cS) current leads. The temperature of the leads decreases from 300 K to 4.5 K when they reach the helium vessel. At this point the current leads are connected to the magnet bus-bars which traverse the λ-plate separating the 4.5 K bath from the 1.9 K bath of the magnets. The level of the LHe bath is regulated to cover the HT_cS part of the current leads and their temperature is controlled by a forced flow of GHe. Externally, a series of warm valves maintain the current leads at their operating temperature and the gas is recovered via a warm line to the recovery line of the refrigerator.

The DFB for String 2 is a prototype similar in size to one of the two types (short) of DFBs that will be present in LHC. The design (mechanical, cryogenic flow scheme, current leads, etc) of the String 2 DFB follows the design of the DFBs which will be present in LHC. The DFB has to withstand the 6.3 ton atmospheric pressure on the endcap.

4.4 The Magnet Protection System

String 2 will be used to :

- qualify the proposed schemes for the protection and discharge of two families of lattice quadrupoles and one of dipole magnets (including their bus-bars) in the LHC machine,
- study magnet-to-magnet quench propagation in a wide sense (dipole-to-dipole, quadrupole-to-dipole, corrector to main magnet, etc.) and,
- study quench detection in the corrector magnet circuits.

Other aspects such as space and installation of equipment as well as choice of the equipment itself will also be investigated.

As for the other components of String 2, all efforts will be deployed to install equipment and components which are as close as possible to the ones which will be finally installed in the collider. In addition, in order to be able to configure the protection system for studies, a certain flexibility that will not be present in the final installation has been foreseen.

Both the fast hardware programmable logic following a quench and the slow time-based controllers for generating the interlocks, which are used in String 1, are taken as reference.

4.5 Quench Detection

As for the collider, the protection of the main magnets of String 2 will be decentralised: each magnet will have its own protection system, fully redundant and independent of all other magnets. When a quench occurs in one of the magnets, the protection system of that magnet will fire the heaters in that particular magnet, shut down the power converters and open the switches across the dump resistors.

Main bus-bars will be divided into half-cell sections and monitored by a redundant self-contained system. If a quench occurs in a bus-bar, the protection system will shut down the power converters and open the switches across the dump resistors, but no heaters will be fired.

A simplified sketch of the Quench Detection System foreseen for the LHC machine is shown in Annex 11. The signal loop named PC loop contains all the hardwired loops to shut down the power converters and open the dump resistor switches.

4.5.1 Quench detection in Main Magnets

The quench detection system for the main dipole and quadrupole magnets will be based on floating bridge detectors where two apertures of each magnet are compared to each other: a quench is detected if the absolute voltage difference between the two apertures increases above a preset threshold. For the quadrupoles, the comparison will be made between two sets of two poles, treating each aperture of the quadrupole as a separate circuit.

In addition to this, the protection system of String 2 includes a programmable matrix, which allows the firing of heaters in all or selected magnets in addition to the heaters of the quenching magnet. The matrix is also capable of providing output signals to, and receive input signals from other String 2 equipment. The matrix is also equipped with a circuit memorising the event or sequence of events leading to a quench.

4.5.2 Quench detection in corrector magnets

The quench detection of the corrector magnets will be carried-out at the cold side of the current leads connected to the circuit. Therefore no signal coming from the voltage taps in the corrector magnets participates to the detection of the quench.

This function is carried out by electronics situated in the power converter racks. However, for the dipole spool pieces, the mid-point of the circuit is connected to a third bus-bar and current lead. This allows, in addition, a bridge detection of a quench.

4.5.3 The Test Controller

The quench detection system of String 2 will also be equipped with an automatic test system, capable of testing the functionality of the whole system including the cabling to the magnets. This test system will make minimal interference with the hardwired nature of the quench detection system.

4.6 Cold By-pass Diodes

The firing of the heaters provokes the commutation of the current towards the parallel cold diodes. Across each double aperture dipole, one diffusion type diode will be installed. There will be three diffusion type diodes from one manufacturer in one half cell and three diffusion type diodes from another manufacturer in the second half-cell.

The maximum reverse voltage U_r across one diode occurs when all dipoles are quenched except one and the magnet chain is de-excited by opening the circuit breaker across the dump resistor. This voltage will not exceed 120 V and is well within the acceptable limits for the diodes. The turn on voltages V_{to} are somewhat higher than for the diffusion diodes used in String 1.

4.7 Quench Heaters and Power Supplies

In order to obtain an even distribution of the energy dissipated in the magnet, both types of main magnets (dipole and quadrupole) are equipped with quench heaters to enhance the normal zone propagation throughout the coils after a quench. Radiation tolerant heater supplies power the resistors by discharging banks of capacitors.

4.8 Discharge Elements: D.C. Circuit Breakers and Dump Resistors

The introduction of two separate 13 kA power circuit for the quadrupole magnets will not require an additional energy extraction system. In fact, the stored magnetic energy of a single quadrupole can be absorbed within its coils in the case of a quench or in the power cables and the free-wheel system in case of a natural current decay.

The existing (String 1) thyristor and mechanical switches and associated dump resistors would meet the demands also for the String 2 dipole chain. However, String 2 represents a unique occasion to obtain operational experience with a prototype of the d.c. breaker facility which is foreseen for the LHC machine. Therefore, this new system will be installed on String 2. The system is composed of:

- eight single-pole, 4 kA-1500 V mechanical circuit breakers, configured in four parallel branches with two series-connected switches. The breakers are manufactured in Russia
- an associated powering and control system, designed and built at CERN
- a current-equalizing power busway for feeding the breaker assembly

An extended test program has been set up in Russia and at CERN for individual testing of the breakers. However, as for most systems, String 2 remains the first and only place, where operational experience can be acquired.

The energy extraction system will be made using a thyristor switch in series with a mechanical switch and a discharge resistor. The value of this resistor can be changed to give different discharge time constants.

The eight breakers of the Russian prototype switch will be delivered mid 1999 and will be installed in String 2 towards the end of that year.

5 Vacuum

The String 2 vacuum systems will be manufactured for the most part from LHC pre-series components. Whilst the LHC-VAC group is not responsible for the procurement of the majority of components making up the vacuum enclosures, it is however responsible for the definition or approval of all vacuum specifications and procedures concerning material selection, cleaning and leak detection.

In order to be representative, the String 2 assembly process should be as close as possible to the foreseen operations in the LHC tunnel, implying a minimum of on-site tasks. Therefore, as for the LHC installation, all String 2 sub-assemblies shall be delivered to the site cleaned and fully vacuum tested.

Vacuum instrumentation will be classified as ‘standard LHC’ or ‘dedicated String 2’.

5.1 Insulation Vacuum

The insulation vacuum of the String 2 will be divided by vacuum barriers into three volumes: the main cryostat containing 8 magnet coldmasses, the QRL, the DFB and the CFB. For the main cryostat and QRL, all LHC insulation vacuum instrumentation will be located at the cryostats of the SSS and the longitudinally adjacent QRL module. Other dedicated String 2 vacuum instrumentation will be distributed along the 107-metre length. As for the String 1, the standard instrumentation flange remains the ISO-K 100. Each of the ports, whether for vacuum or other instrumentation, will be coded and have a predefined use. The permanently installed vacuum instrumentation shall be similar for each volume and will include a turbomolecular pumping group, total pressure gauges, isolation valves, and over pressure safety valve. By-pass manifolds equipped with remote control valves will be installed at each vacuum barrier. For dedicated String 2 experiments, additional vacuum instrumentation will installed. This will include helium leak simulators at magnet interconnects, activated charcoal, pressure gauges within the MLI blankets, and residual gas analyser (RGA). Mobile vacuum instrumentation is also required for cryostat evacuation and leak detection, and will conform to LHC tunnel *stay clear* zones.

5.2 Beam Vacuum

The beam vacuum system consists of two independent cold bores. In-line with the present beam vacuum baseline design, all of the cold system will be welded. The room temperature pumping manifold at the SSS will remain all-metal, based upon Conflat® demountable flanges.

Unlike String 1, the beam vacuum will be fully equipped with beam screens and intermagnet RF junctions, and will be assembled according to UHV procedures. Twelve 15 metre dipole beam screens and four 6 metre SSS beam screens are foreseen, the latter being an integrated unit with the beam position monitor. In order to simulate proton beam heating effects, heaters will be attached to the beam screens and BPMs.

The permanent beam vacuum instrumentation will be located on the pumping manifold at the SSS, with a set of total pressure gauges, ion pump, rupture disc, isolation valve and roughing valve for each beam tube. For dedicated String 2 experiments a mass spectrometer (RGA) will be installed.

5.3 Beam screen and BPM measurements

Thermal and mechanical measurements of the beam screens and the BPMs will be necessary. At least two dipole beam screens, two SSS beam screens, one magnet interconnect and one BPM will be equipped with dedicated sensors. The integration of the sensors required for the measurements may imply minor design deviations for some of the vacuum component. Similar to the two prototype beam screens installed on String 1, the measurements will concern component performance during cool down, warm up, current ramping, steady state operation, and magnet quenches.

5.4 Leak detection

Leak detection of the vacuum systems will be achieved in 3 stages; individual testing of each new in-situ joint, global testing per vacuum enclosure with helium circuits pressurised, and global testing per vacuum enclosure during the cooldown. Unlike String 1, clam shell tooling will be available for individual leak testing the welds of pressurised helium lines, giving greater sensitivity and saving time. In addition, a method to longitudinally locate helium leaks to an interconnect during global leak testing is under elaboration and will be employed on String 2.

The leak testing operations require collaboration between many groups including LHC-ACR, LHC-CRI, LHC-VAC and TIS/GS. The written procedures adopted for String 1 will be further elaborated.

6 Monitoring and Control

As it was the case for String 1, the String 2 experimental facility will be equipped with a control system and a separate data acquisition system.

The control architecture of String 2 will be mixed: for all the aspects related to the deterministic control of the power converters it is based on in-house developments inspired on commercial products whereas, for process control and supervision it is based on industrial control system architecture.

6.1 Data Acquisition

The data acquisition system of String 1, which provides archiving and transient recording will be re-used for String 2. The channel number will be increased to 860. Each channel is an independently configurable 16-bit ADC that can run up to 1 kHz and acquire up to 3500 samples per event. Additional hardware to push the sample size to 14000 per channel can be installed.

The data acquisition system also includes a configurable cluster of 20 channels at 50 kHz for special magnet protection studies.

The data from the sensors is converted to physical units via a variety of conversion functions (polynomials, exponential functions, etc) and conversion tables providing linear interpolation between points.

The data acquisition system is synchronised to the millisecond with the LHC control system and to the second with the process control system for cryogenics and vacuum.

6.2 Data Storage System

Following the experience on String 1, a central data storage system, based on a combination of flat files and Oracle® tables, serves as repository for all the data acquired by different systems (general data acquisition, process supervision, special data acquisition systems, LHC control system) connected to String 2.

A standard network interface provides the means to retrieve raw and converted data for processing and display.

6.3 Process Control

Both the process control and the supervision of the cryogenic and the vacuum systems will be based on industrial control systems.

6.3.1 Process Control for the String Cryogenics

The main control parameter of the ring cryogenic system is the magnet temperatures. This control is difficult because the physical process is involved strongly non-linear and cryogenic thermometers exhibit many undesirable characteristics that affect their long-term performance. The requirements on the thermometer accuracy will define the periodicity of in-situ re-calibration campaigns during which the LHC will not available for physics. In order to increase the operational margins either on the temperature measurement or on the cooling system capacity more advanced controllers are being studied, if these technique are successful they should result in a narrower temperature control band when compared to a standard PID controller. The type of controllers that are being investigated include *grey* or *black box system identification* and *model based predictive controllers*. These techniques produce a simplified model of the process that is then used to generate the optimum feedback control signal.

In addition to the magnets temperature control, several other closed control loops exist and they will be implemented by using standard PID controllers. The transient behaviour will also be investigated in order to develop fast cool-down, warm-up and quench recovery.

A large number of cryogenic sensors will be distributed around the 27 km of the circumference of LHC. String 2 will be used to demonstrate, test and validate the different signal conditioning units and their data transmission system feeding the programmable logic controllers.

6.3.2 Process Control of the Cryogenic Plant

The software methodology that has been adopted to control the external cryogenics for String 2 (i.e. compressors, cold box, LN_2 precooler and Cryogenic Feed Box) is based on an object-oriented approach, similar to the one already used for SPS and LEP2 cryoplants.

The software will be structured in four different levels: I, IIa, IIb and III. Control level I is the highest one, while control level III is the lowest. The philosophy is that every high-level object links a group of lower-level objects to obtain a certain degree of automation.

The pyramidal structure of the software is shown in Annex 12. Level III objects are simple physical entities like valves, vacuum pumps, heaters, etc. They do not need any operational logic since they can function on their own. Actually, most of the cryoplant logic is contained in the two intermediate levels called IIa and IIb. But, while level IIb links objects of level III to constitute sub-components of the cryoplant (the vacuum system, the turbines circuits, the Joule-Thomson circuit, etc.), level IIa controls the main components like the compressors, the cold box and the precooler. Finally, the supervision of the entire cryoplant is performed by the highest level I.

6.3.3 Controls for Vacuum

For String 1, a vacuum Programmable Logic Controller (PLC) was used to acquire the status and data values of the vacuum instrumentation and provide an interface with the supervision software. For String 2, the vacuum PLC will provide the additional functions of process control and remote operations. The PLC will be positioned under the central dipole of a half-cell in accordance with current recommendations.

6.3.4 Deterministic Control of the Power Converters

The LHC Dynamic Effects Working Group has brought attention to the requirement for deterministic control facilities for the LHC. Potential areas where such techniques may be employed include:

- tracking of the main dipole powering circuits,
- closed orbit control during snapback at the early part of the ramp,
- compensation of non reproducible sources of tune and chromaticity variation on the ramp.

The response of the power converter control loops is chosen such that an error signal, derived from the above effects, can be introduced with a useful bandwidth of 50 Hz. Prototype development for the power converter control electronics is based upon the premise that all converters will accept such an error signal.

Plenary

Date of Meeting	Topics Discussed
April 16th 1996	First Meeting : Setting the Scene
June 20th 1996	Magnetic Measurements on String 2
August 29th 1996	Review
February 13th 1997	Simplification du Schéma Cryogénique String 2 Schedule
April 24th 1997	String 2 Version 1 challanged

Powering & Magnet Protection (Chairman : P.Proudlock)

Date of Meeting	Topics Discussed
April 25th 1996	Functionalities of the Powering System for Version 1 Floor Space for Power Converters
July 4th 1996	Electrical Circuits for Version 1 and String 2000
September 12th 1996	HT_CSCurrent Leads: State of the Art
November 21st 1996	Electrical Circuit Diagram for String 2000 Floor Space DFB
March 27th 1997	Quench Detection and Magnet protection for String 2

Cryogenics & Vacuum (Chairman : W.Erdt)

Date of Meeting	Topics Discussed
May 9th 1996	Description of the Vacuum and Cryogenic Systems for String 2
September 26th 1996	The QRL for String 2
December 5th 1996	The Cryogenic Scheme for String 2
March 13th 1997	The Vacuum of String 2000

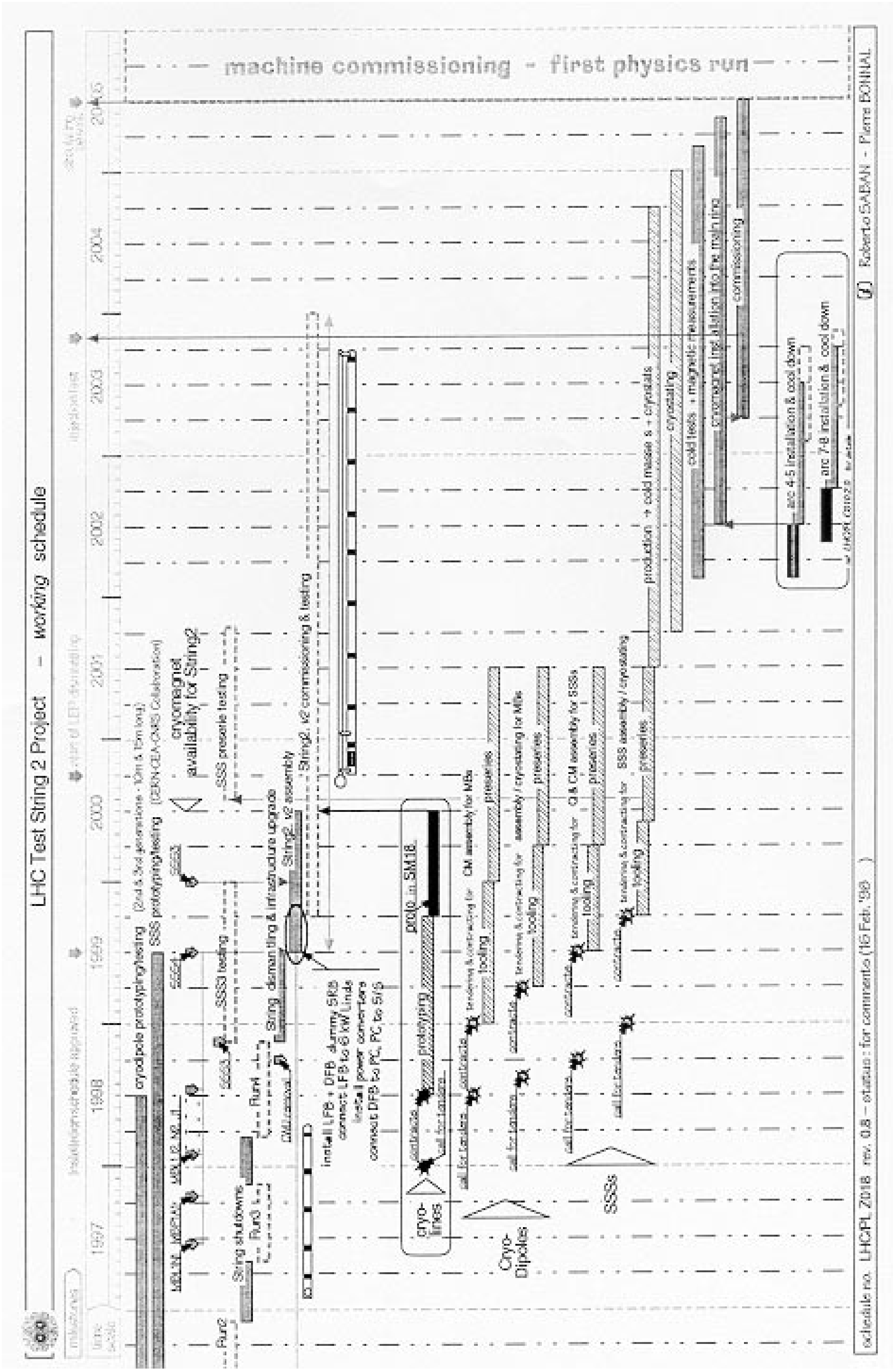
Magnets & Mechanics (Chairman : A.Poncet)

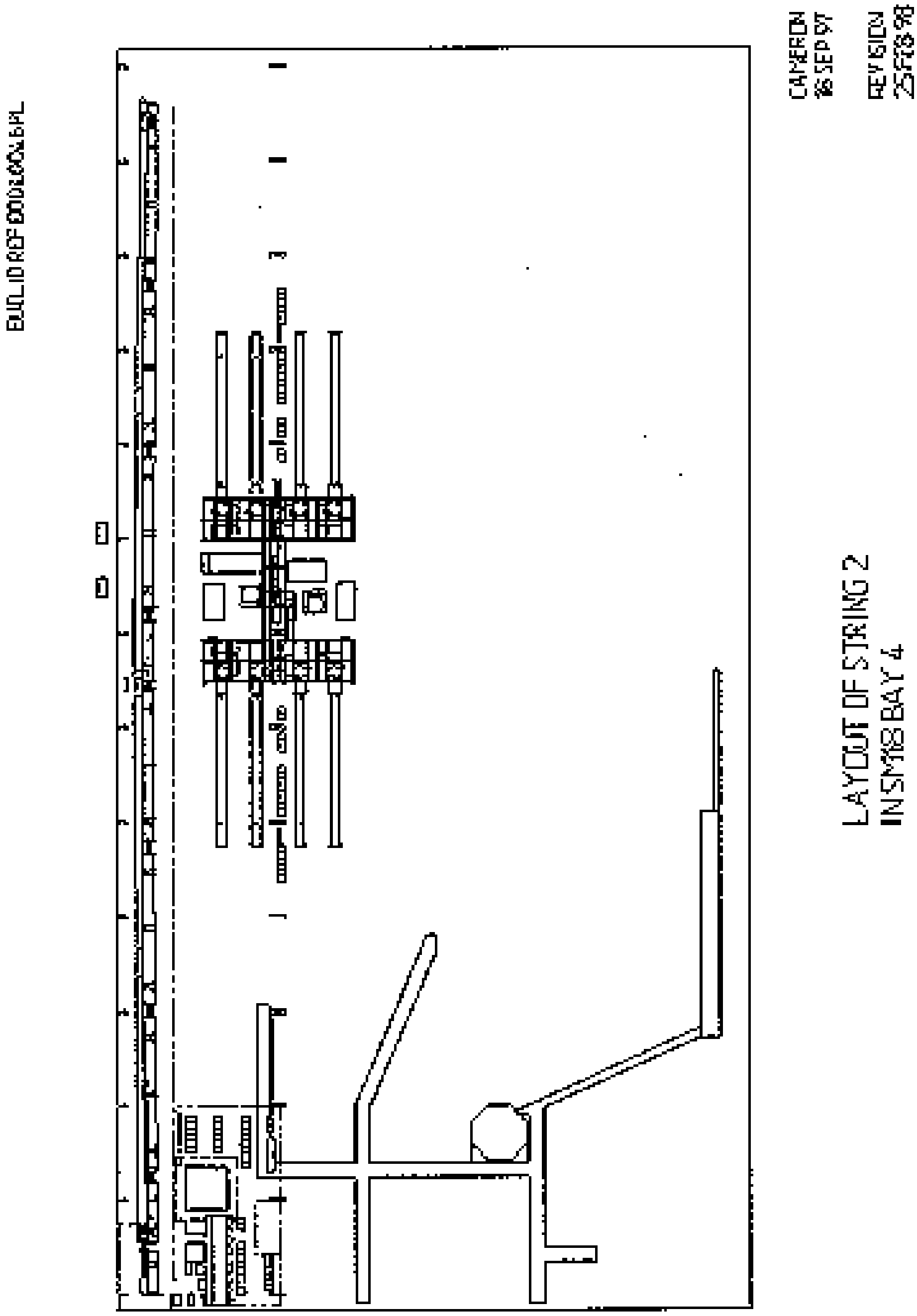
Date of Meeting	Topics Discussed
May 23rd 1996	Dipoles, SSS's and DFBs
August 1st 1996	Magnet Interconnects
December 19th 1996	Status of the Dipoles, the SSS's and the DFBs
March 27th 1997	Layout of String 2000

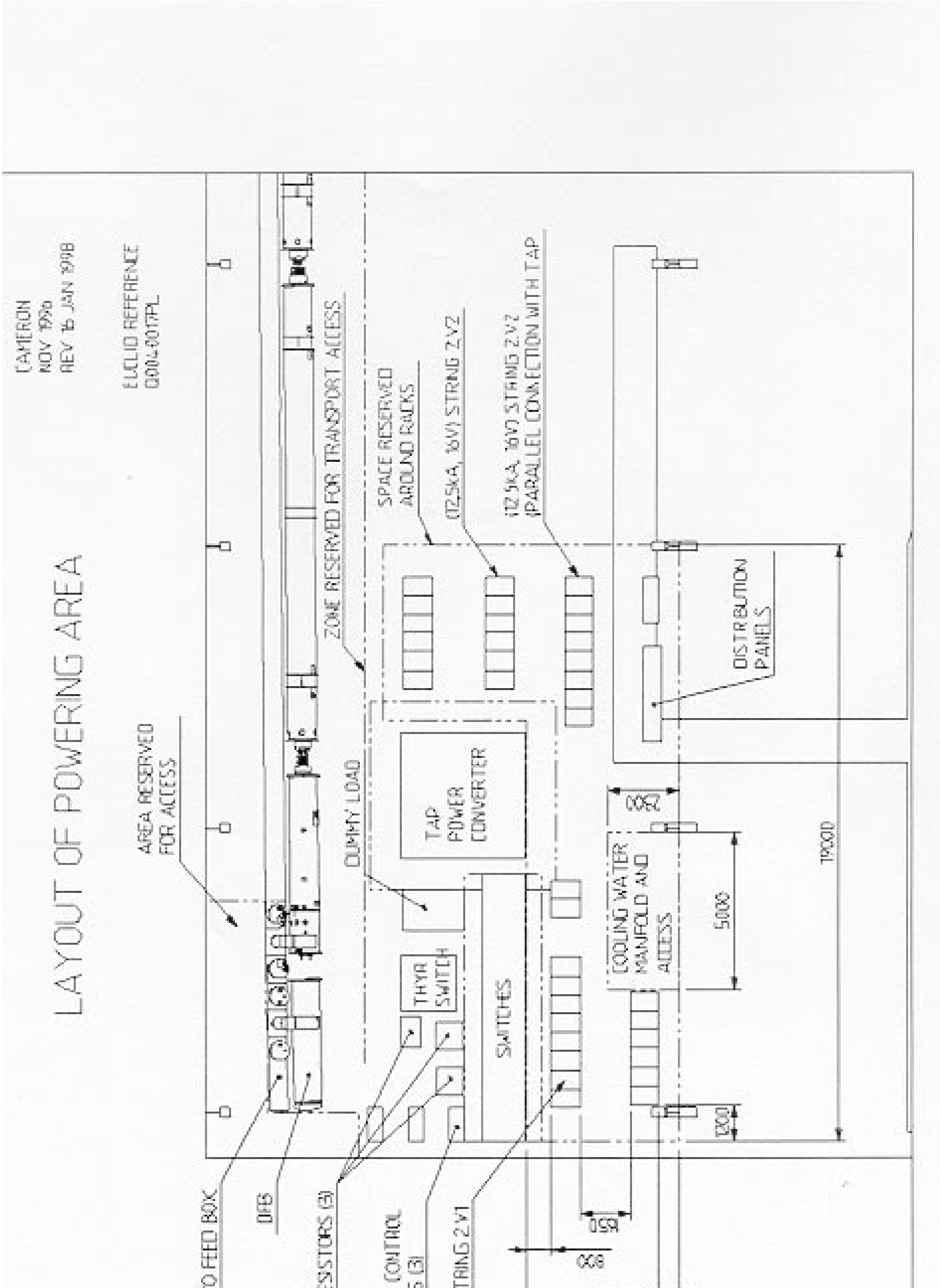
Instrumentation & Controls (Chairman : R.Saban)

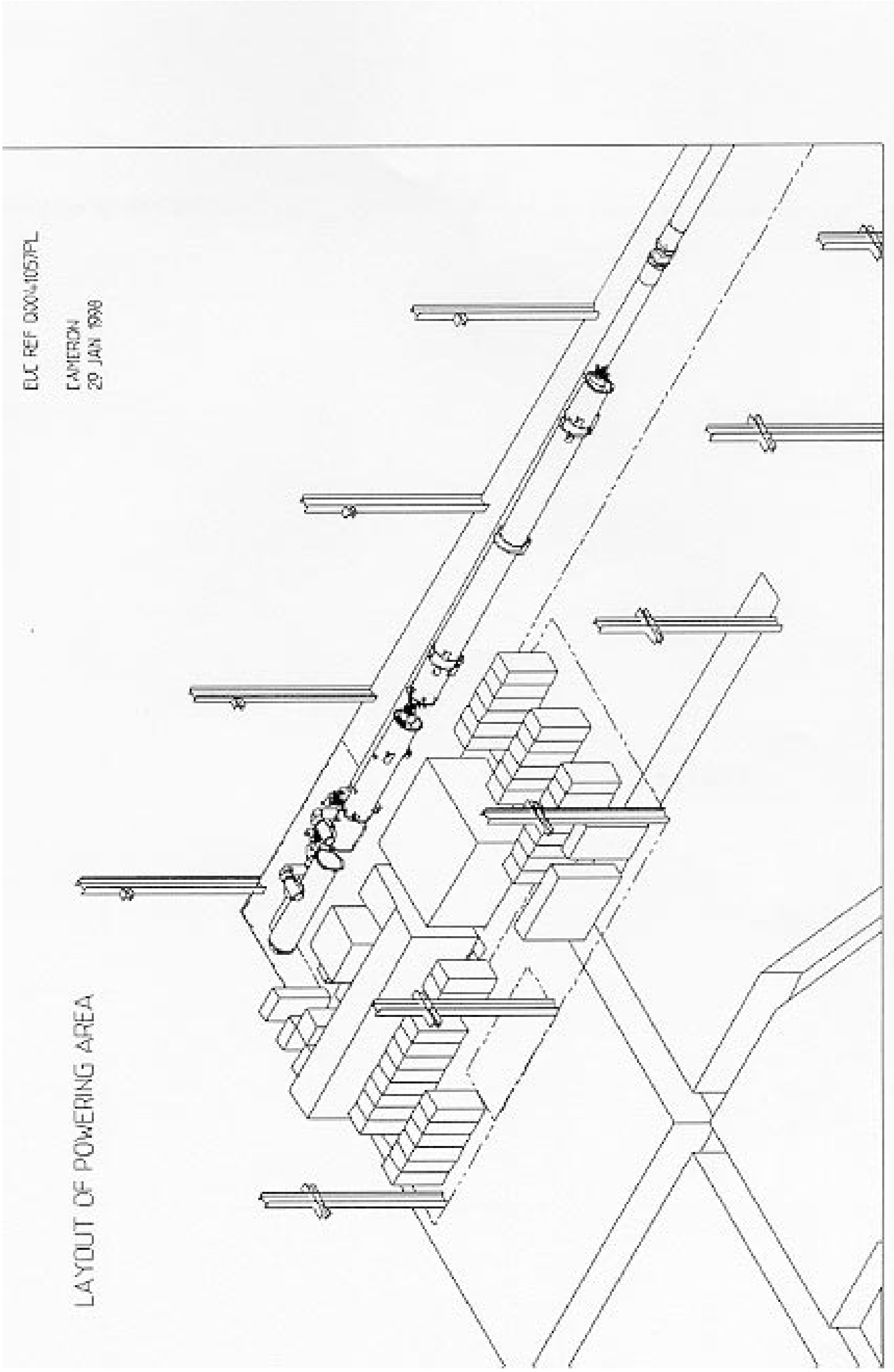
Date of Meeting	Topics Discussed
June 6th 1996	Review of the Instrumentation of String 2
August 15th 1996	Controls & Fast Feedback
January 16th 1997	The 6kW Linde Cold Box
April 10th 1997	The Data Acquisition System for String 2000 The Data Storage System

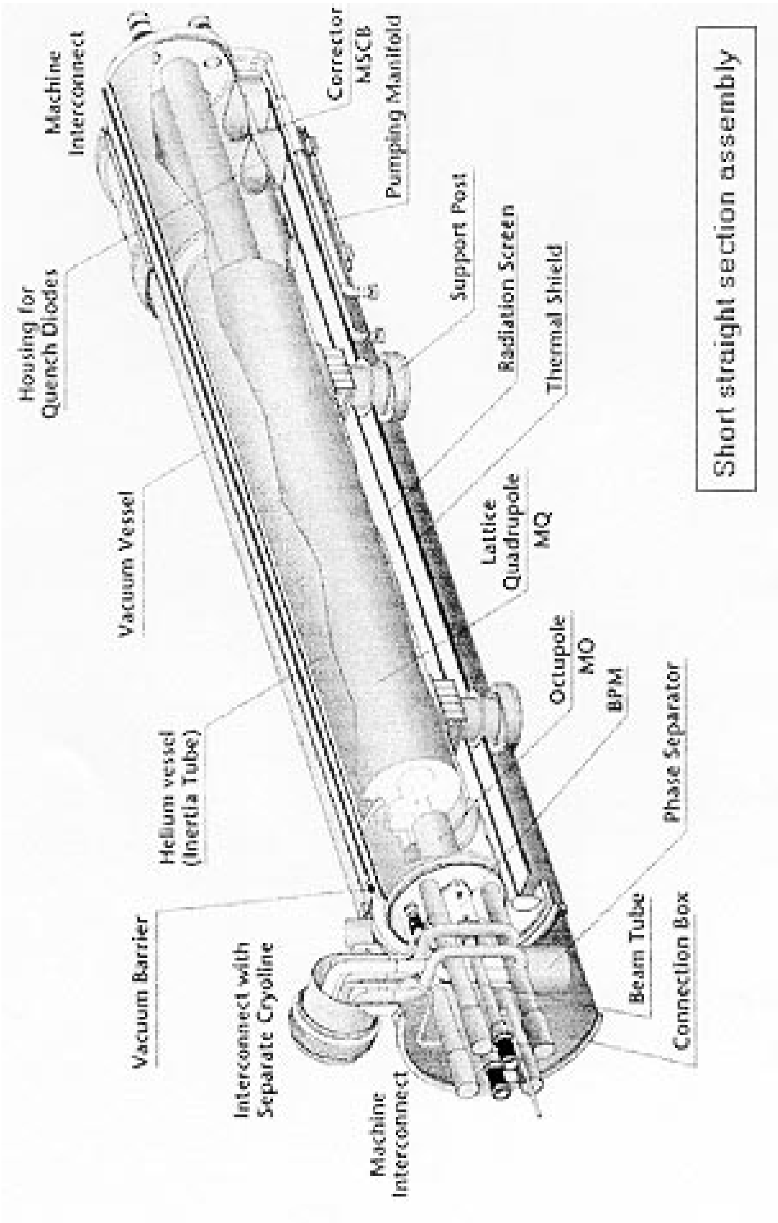
A.Ballarino
A.Bézaguet
JC.Billy
H.Blessing
M.Bona
P.Bonnal
F.Bordry
JC.Brunet
W.Cameron
J.Casas-Cubillos
L.Coull
P.Cruikshank
K.Dahlerup-Petersen
JP.Dauvergne
N.Delruelle
W.Erdt
P.Faugeras
G.Fernqvist
H.Gaillard
R.Gavaggio
T.Goiffon
P.Gomes
M.Granier
D.Hagedorn
K.Henrichsen
B.Hilbert
A.Ijspeert
B.Jenninger
S.Knoops
W.Koelemeijer
JP.Koutchouk
J.Kragh
HK.Kuhn
R.Lauckner
P.Lebrun
D.Leroy
A.Mathewson
D.Missiaen
F.Momal
L.Oberli
R.Parker
V.Parma
J.Pedersen
JL.Perinet-Marquet
D.Perini
M.Peryt
J.Pett
A.Poncet
P.Proudlock
P.Provenaz
JP.Quesnel
M.Rabany
D.Richter
F.Rodriguez-Mateos
P.Rohmig
G.Riddone
A.Rijllart
R.Saban
Ph.Sacré
R.Schmidt
L.Serio
CH.Sicard
A.Siemko
P.Sievers
P.Strubin
A.Suraci
L.Tavian
U.Wagner
L.Walckiers
R.van Weelderen
L.Williams.

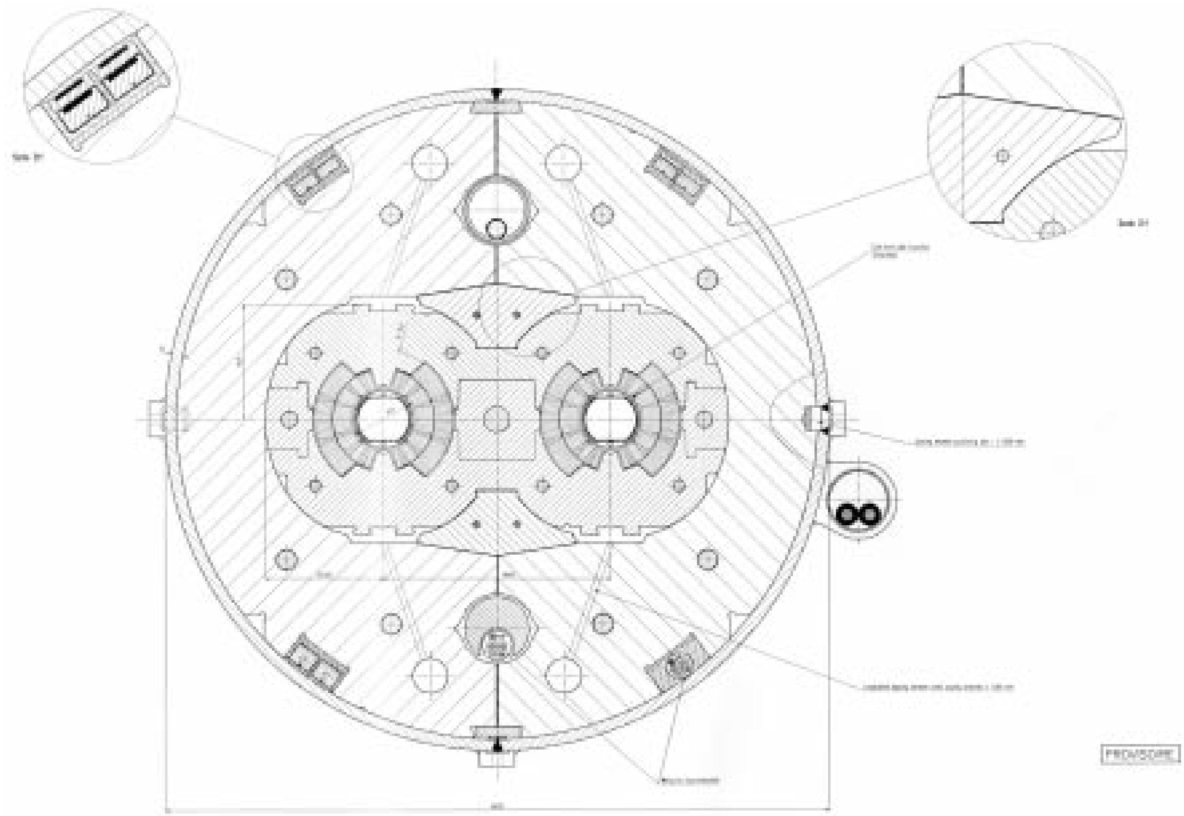

LHC Test String 2 Project - working schedule
machine commissioning - first physics run

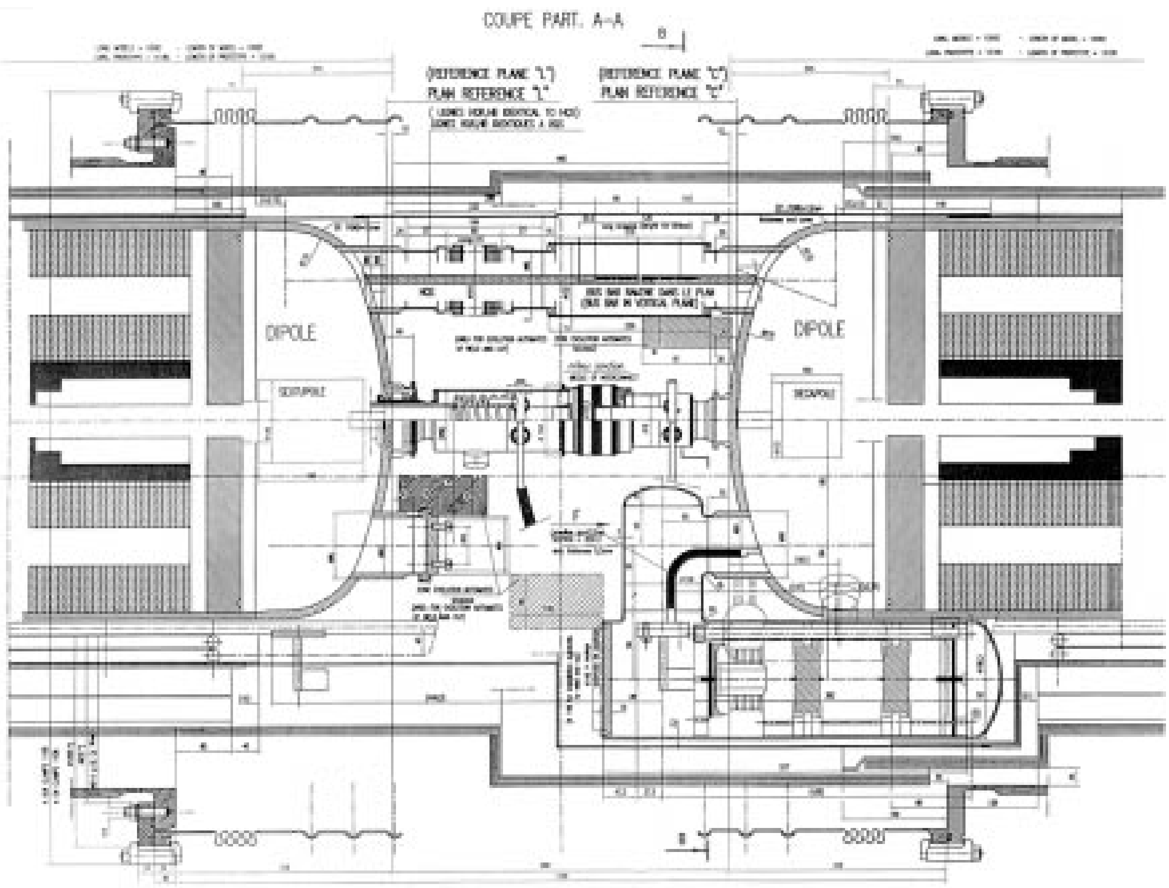

CAMERON
16 SEP 97
REVISION
25 FEB 98
LAYOUT OF STRING 2
IN SM18 BAY 4

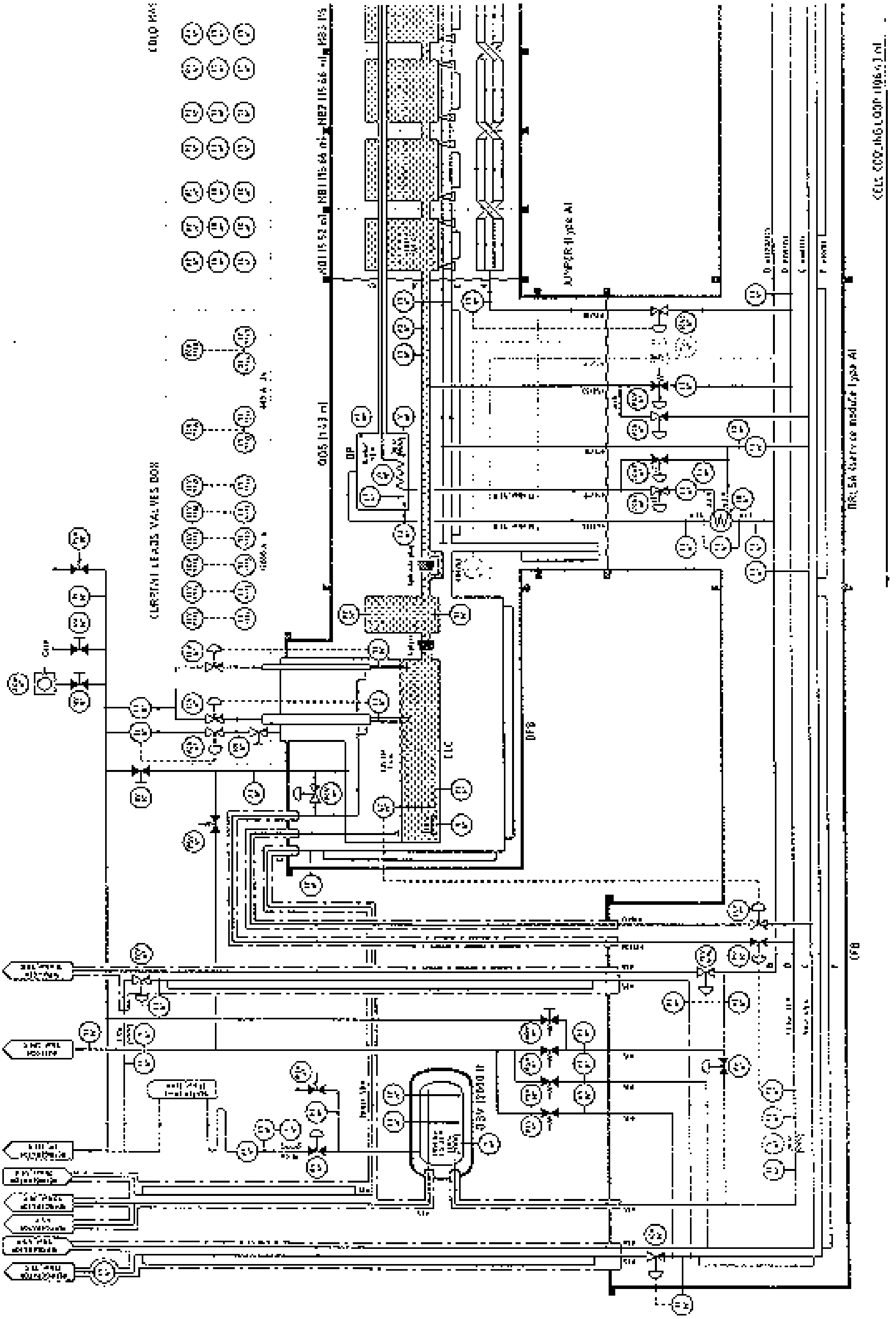

LAYOUT OF POWERING AREA
CAMERON
NOV 1996
REV 16 JAN 1998
EUCLID REFERENCE
AREA RESERVED FOR ACCESS
ZONE RESERVED FOR TRANSPORT ACCESS
SPACE RESERVED AROUND RACKS
(12.5kA, 16V) STRING 2 V2
(12.5kA, 16V) STRING 2 V2
(PARALLEL CONNECTION WITH TAP
DUMMY LOAD
TAP POWER CONVERTER
DISTRIBUTION PANELS
COOLING WATER MANIFOLD AND ACCESS
THYR SWITCH
SWITCHES
CRYO FEED BOX
DFB
DUMP RESISTORS (3)
PROCESS CONTROL CABINETS (3)
12.5kA, 16V STRING 2 V1
2300
5000
19000
1200
650
800
650
4900

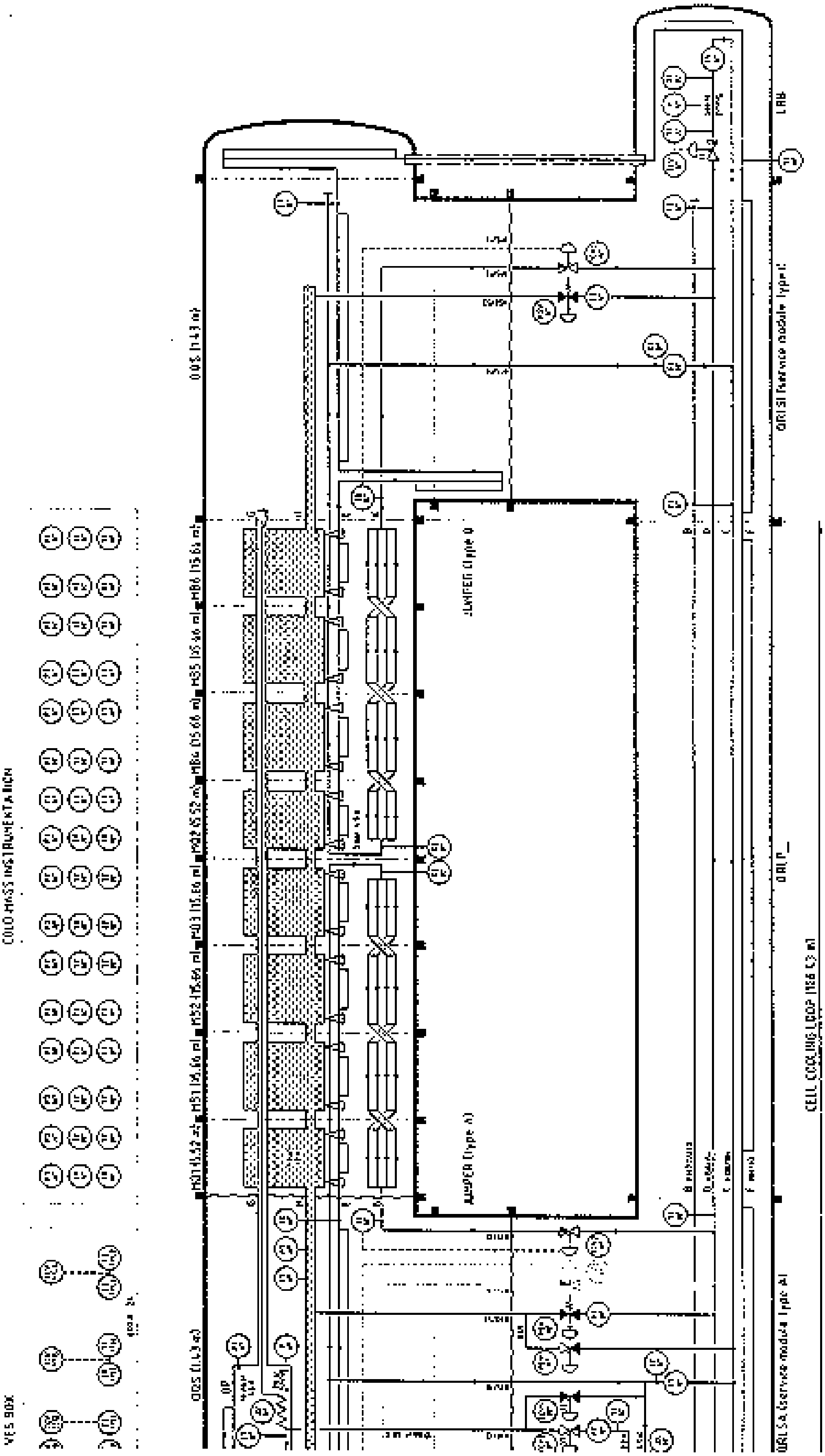

LAYOUT OF POWERING AREA
CAMERON


Machine Interconnect
Housing for Quench Diodes
Vacuum Vessel
Helium vessel (Inertia Tube)
Vacuum Barrier
Interconnect with Separate Cryoline
Machine Interconnect
Corrector MSCB
Pumping Manifold
Support Post
Radiation Screen
Thermal Shield
Lattice Quadrupole MQ
Octupole MO
BPM
Phase Separator
Beam Tube
Connection Box
Short straight section assembly


PROVISOIRE

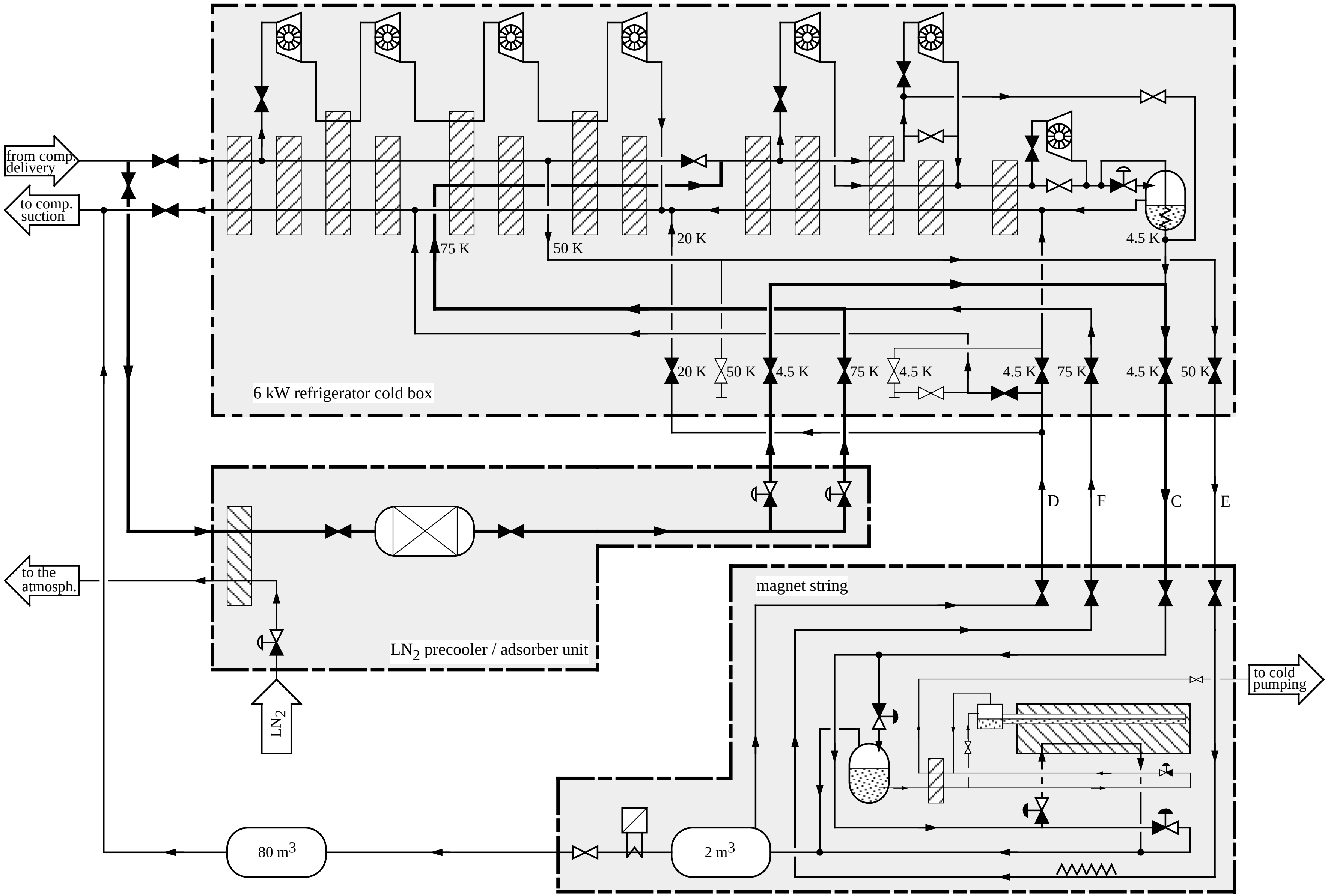

COUPE PART. A–A
(REFERENCE PLANE "L")
PLAN REFERENCE "L"
(REFERENCE PLANE "C")
PLAN REFERENCE "C"
DIPOLE
DIPOLE

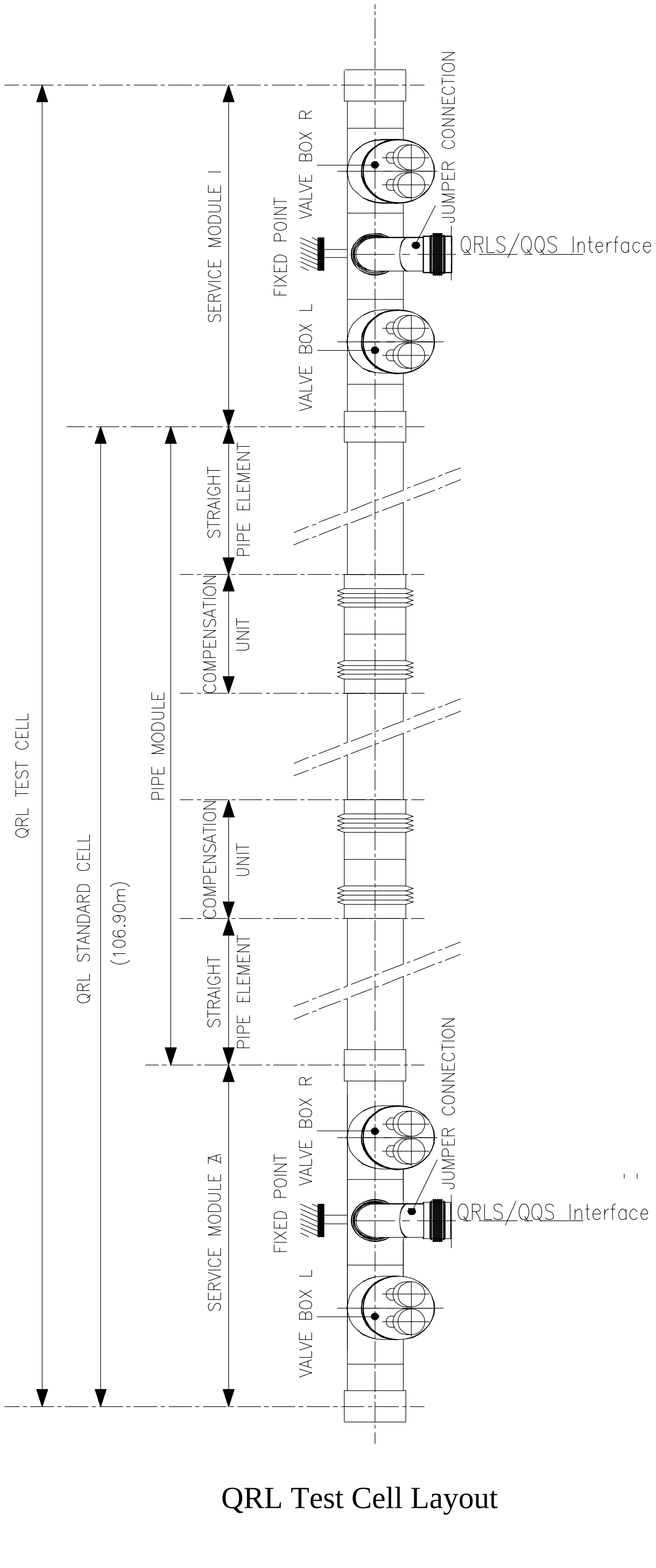

CURRENT LEADS VALVES BOX
DFB
CLC



	Heat loads		Equivalent entropy flux	
non-isothermal load between 50 K and 75 K	700	[W]	11.3	[$J.s^{-1}.K^{-1}$]
non-isothermal load between 4.5 K and 20 K	160	[W]	17.4	[$J.s^{-1}.K^{-1}$]
isothermal load (refrigeration) at 1.9 K	50	[W]	25.7	[$J.s^{-1}.K^{-1}$]
Version1 liquefaction rate at 3 bar and 4.5 K (6 ∗ 13 kA + 24 ∗ 600 A of classical leads)	12	[$g.s^{-1}$]	332.6	[$J.s^{-1}.K^{-1}$]
Version 2 liquefaction rate at 3 bar and 4.5 K (6 ∗ 13 kA + 24 ∗ 600 A of HT_C leads)	7.5	[$g.s^{-1}$]	207.9	[$J.s^{-1}.K^{-1}$]

Table 1: The heat loads converted to an equivalent entropy flux used for sizing the cryoplant


from comp. delivery
to comp. suction
to the atmosph.
LN2
6 kW refrigerator cold box
75 K
50 K
20 K
4.5 K
20 K
50 K
4.5 K
75 K
4.5 K
4.5 K
75 K
4.5 K
50 K
D
F
C
E
LN2 precooler / adsorber unit
magnet string
to cold pumping
80 m3
2 m3



QRL Test Cell Layout

Table 2 : Dimensions and nominal operating conditions of the QRL headers

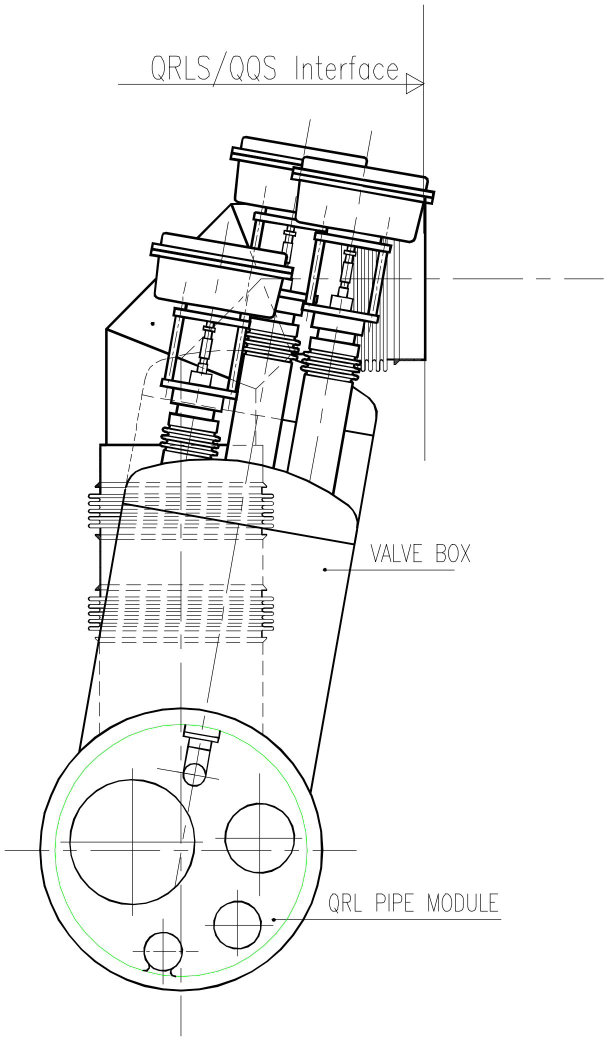
Header	Description	Outer diameter [mm]	Inner diameter [mm]	Nominal temperature [K]	Nominal pressure [bar]
B	Pumping return	273	267	3.8-4.2	0.016
C	4.5 K supply	104	100	4.6	3.6
D	20 K return	154	150	20	1.3
F	75 K return	83	80	65-75	19

Table 3: Service Module Type A

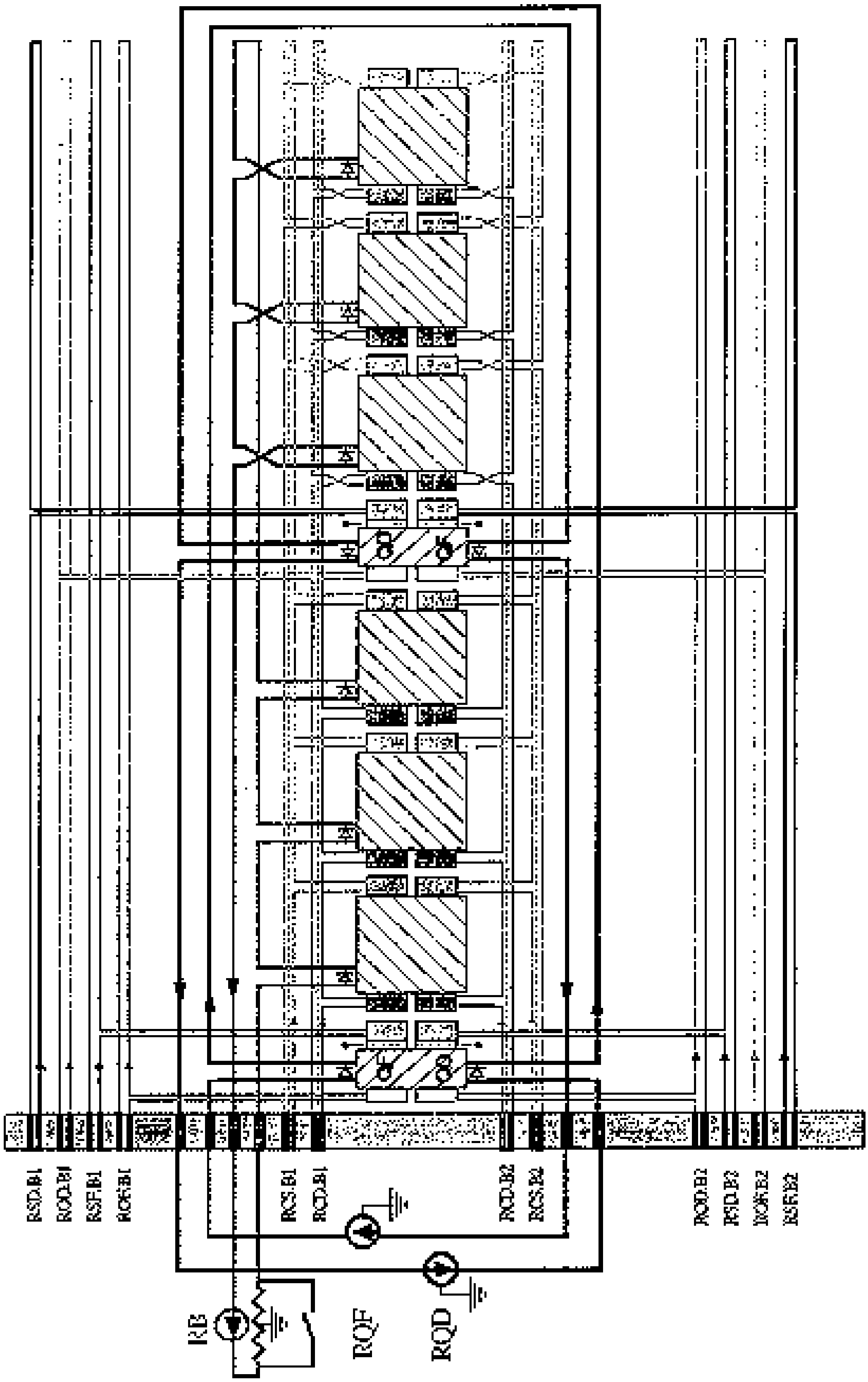
Cryogenic circuit	Interconnect pipes		Valves	
	Number	Diameter [mm]	Type	DN [mm]
1.9 K pressurised He supply	1	53x1.5	CFV (SRV)	32 (50)
1.9 K saturated He supply	1	12x1	TCV10 TCV11	6 6
1.9 K saturated He return	1	64x2		
4.5 K supply	2	18x1.5		
4.5 K return	1	18x1.5	TCV40 TCV41	6 6

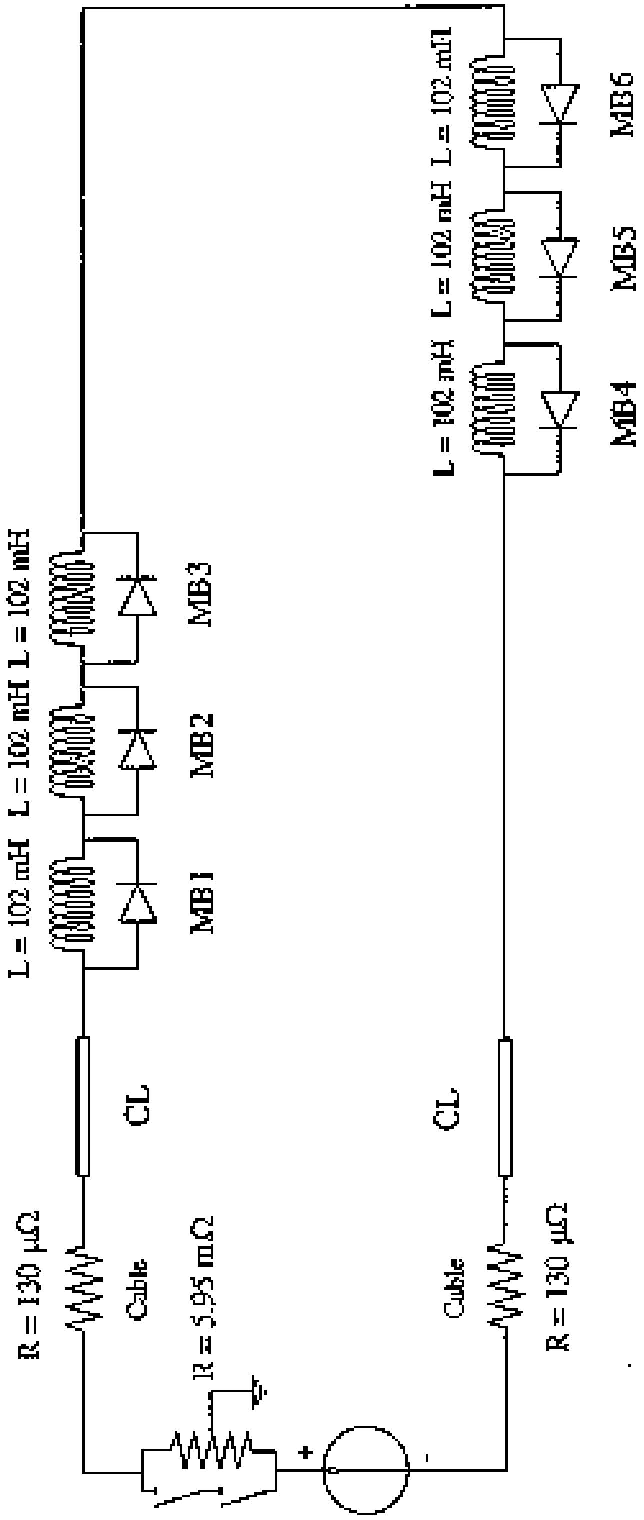
Table 4: Service Module Type I

Cryogenic circuit	Interconnect pipes		Valves	
	Number	Diameter [mm]	Type	DN [mm]
1.9 K pressurised He return	1	53x1.5	SRV	50
4.5 K supply	1	18x1.5		
4.5 K return	1	18x1.5	TCV40	6

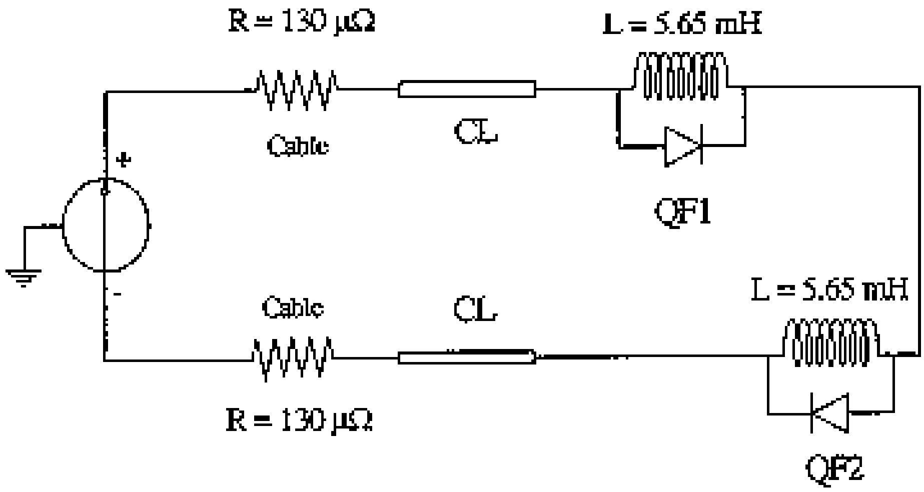


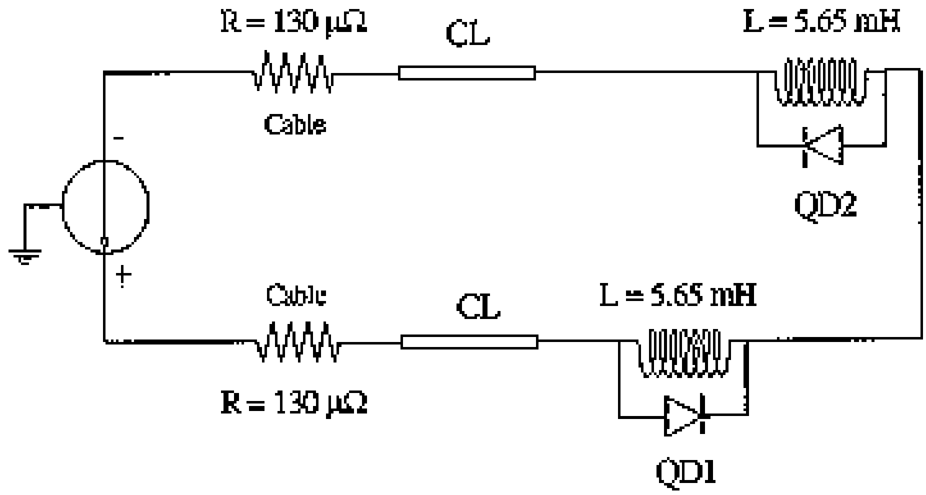
Schematic transverse view of the QRL Test Cell


RB
RQF
RQD

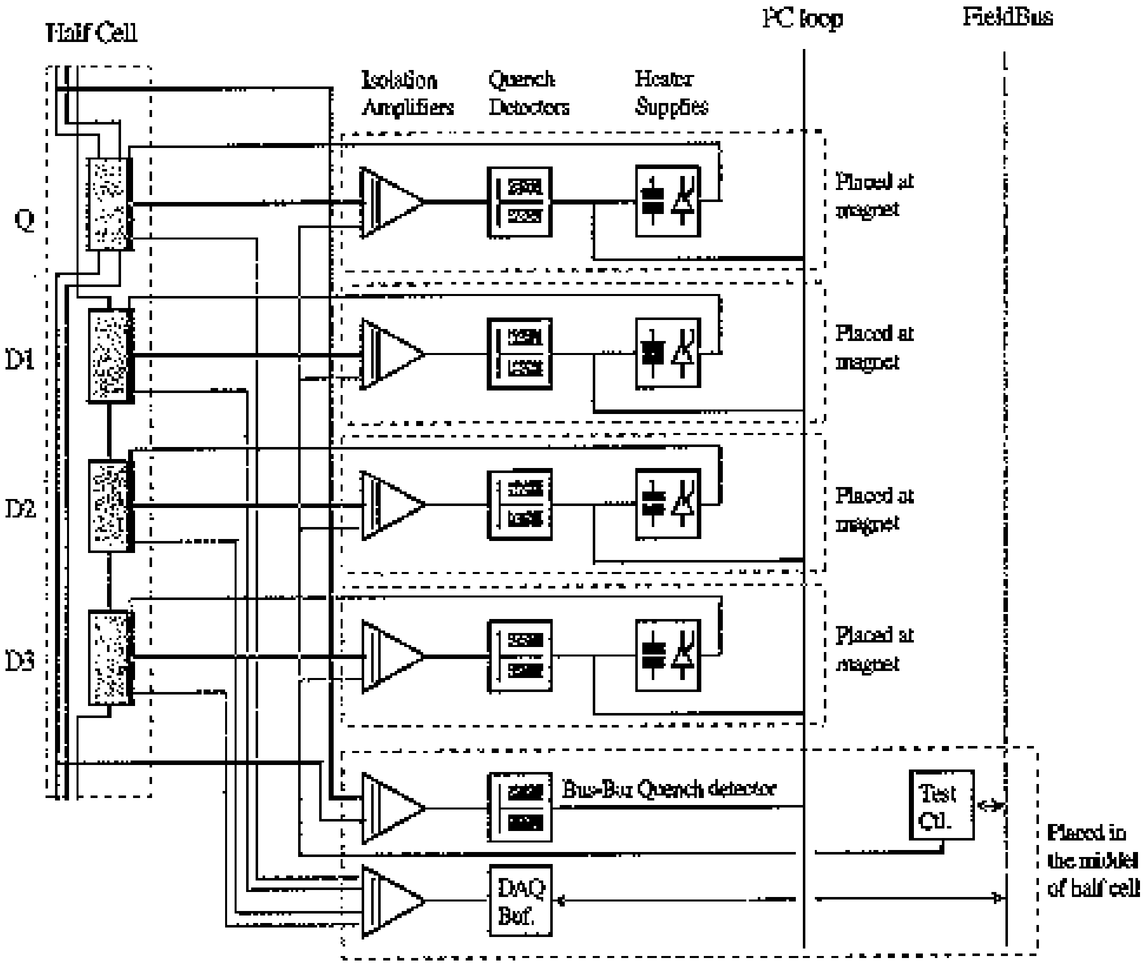


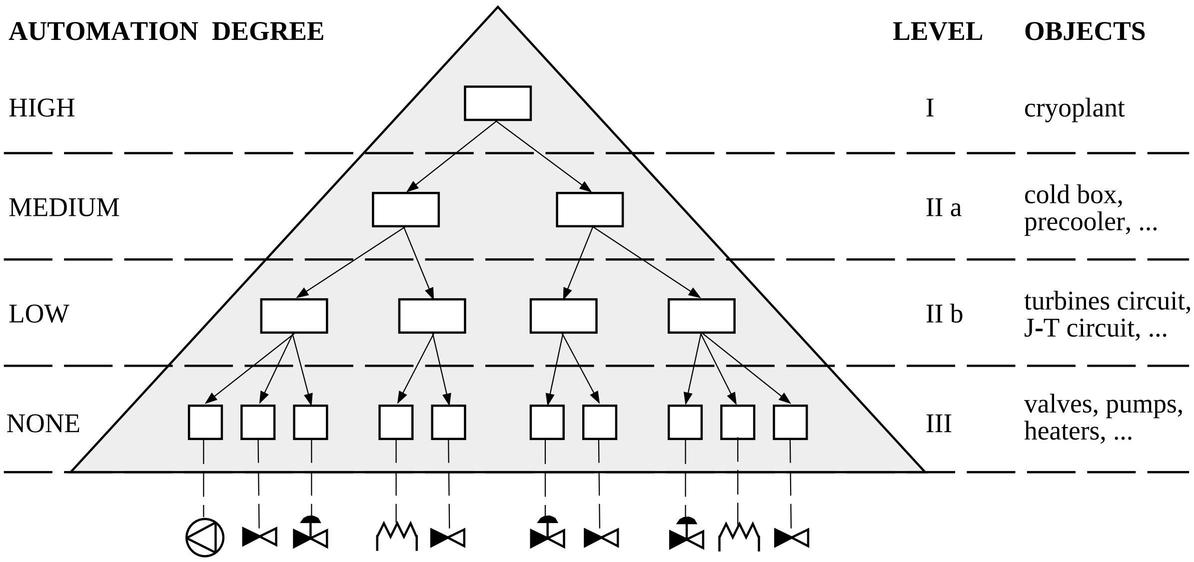
DIPOLE ELECTRICAL CIRCUIT DIAGRAM





QUADRUPOLE ELECTRICAL CIRCUIT DIAGRAMS


Half Cell
PC loop
FieldBus
Isolation Amplifiers
Quench Detectors
Heater Supplies
Q
D1
D2
D3
Placed at magnet
Placed at magnet
Placed at magnet
Placed at magnet
Bus-Bar Quench detector
Test Ctl.
DAQ Buf.
Placed in the middle of half cell


AUTOMATION DEGREE
LEVEL
OBJECTS
HIGH
I
cryoplant
MEDIUM
II a
cold box,
precooler, ...
LOW
II b
turbines circuit,
J-T circuit, ...
NONE
III
valves, pumps,
heaters, ...