A 20 kA TEST BENCH FOR HIGH-PRECISION CURRENT MEASUREMENTS

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INTRODUCTION

With the LHC proton collider, presently entering its phase of construction at the Cern site, Geneva, unprecedented precision requirements are being defined for the measurement, setting and adjustment of the d.c. currents, feeding the superconducting magnets, up to the ultimate current level of the machine (13 kA) and that of certain experimental magnets (20 kA). Compared to previous accelerators at Cern (e.g. the present front-line collider LEP), demands in terms of current measurement, setting and tracking precision of the LHC dipole- and quadrupole chains are increased by a factor of ten, to attain a few ppm only -and this for currents, which are almost three times higher.

The currents of the magnet chains will be measured by state-of-the-art, zero-flux DCCT's, designed and manufactured by a number of European companies. As no existing laboratory in the world would be capable of performing the calibrations of these transducers to the required precision, it became evident that a major upgrading of the Cern's current Standards laboratory was needed.

The purpose of the new test facility is to evaluate DCCT's from various manufacturers, in order to compare and select the products. It should equally be a calibration facility for determination of offsets, linearity and drift. Furthermore, it should provide the means to study the sensitivity of the transducers to the external stray fields, for which the busbars around the DCCT are the principal source (ref. 1). Consequently, the test bench should provide easy means to modify the busbar arrangements around the transducer coil. In order to provide a high degree of reproducibility of the current distribution in the return bars and consequently, of the field picture around the test objects, the automatic clamping mechanisms must feature highly reproducible contact resistance values, -and this also after a high number of operations.

In view of the significant number of transducers to be evaluated and calibrated (probably several hundred units per year) it was of major importance to design and construct a test facility, which is highly automated, with the ultimate goal of being operated by a single technician, -from the assisted loading of the up to 80 kg heavy transducer coils, automatic opening and closing of the 20 kA test cell to the data acquisition system. Because of these requirements, all connections, subjected to frequent opening and closing, are based on reliable, pneumatically operated, lamella equipped clamps, without any bolted joints.

Finally, the facility should be a test bench for evaluation of different busbar configurations in view of their use for the transport of heavy currents in the LHC machine.

1. COMPOSITION AND CONCEPT

1.1 General layout

The following items constitute the principal components of the power part of the new Standards laboratory: A 20 kA d.c., new generation power converter, featuring primary soft switching technology with IGBT's operating at 20 kHz switching frequency in a full-bridge topology ("Danfysik", SYSTEM 8800), an associated quasi-coaxial cage, known as the regulation cell, housing the transducer coils of the two DCCT's, which are used for setting and regulation of the power converter output current, a 20 kA, motor-driven current inverting switch ("Argus/ Multi-Contact"), which will facilitate the checking of linearity and zero offsets in the test object, a series-connected current reference transducer (a so-called 'range-extender' from "Measurements International MIL"), a cage containing the reference DCCT's (the so-called reference cell), the complex measuring cell, into which the transducers to be calibrated are mounted, and finally the 20 kA busway, which makes up the d.c. power link between the elements of the facility. The relative position of the various components is given in fig.1.

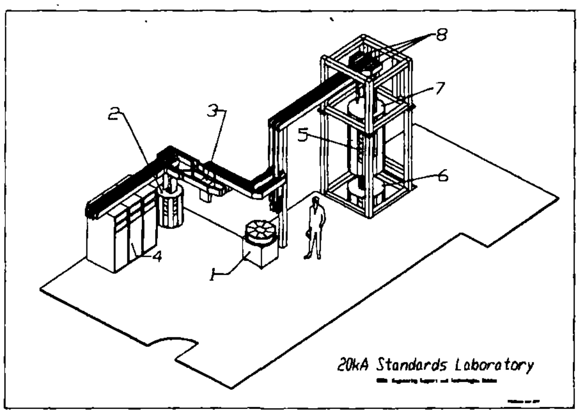

Figure 1. General view of the new Standards Laboratory. (1:Range extender, 2: Regulation Cell, 3: Inverting Switch, 4: Power Converter, 5: DCCT, 6: Reference Cell, 7: Measuring Cell, 8: Automatic Clamps)

High precision, high current transducers are sensitive to field variations around the toroidal coils, as generated between the central busbar and the current return bars or by stray fields from adjacent conductors. Depending on the design and internal magnetic shielding, the transducer coils may deviate from their usual characteristics or even totally misbehave if gradients as low as 3 mT occur around the circumference of the coil. If measures are not taken during the design of the adjacent conductors, such levels may easily be attained. This is the reason why the three transducer cells closely simulate a coaxial configuration and why the bus bar arrangement is more complex than a simple bi-polar structure.

1.2 The power busway – field confinement

Because of the above considerations, the issues of field confinement and symmetry were in the centre of the bus bar and cell design studies. Hollow copper rods for direct water cooling were used for the central conductors of the cells, whereas single or arrays of natural air cooled, flat bars were used for the interconnecting busway as well as for the vertical return bars of the cells. This choice was made in order to study the thermal and field behaviour of such elements in view of their potential use for transport of high d.c. currents in the LHC machine, where a global performance and cost optimisation of these components is essential.

The program 'FLUX2D' was used for calculation of the main- and stray fields around the various conductor arrangements. Intuitively, parallel bus bars or cables, carrying currents in opposite directions shall be mounted in close pairs in order to confine the field to a limited volume. For a given current, the stray field outside the bus pair in a given location and direction will depend on the degree of confinement and, to a lesser extent, of the form and size of the bars. The calculations clearly showed the significant reduction in the stray field obtained by re-arranging the conductors, so that the main field is split into two confined areas. The reduction is typically a factor of 25 at one meter distance for an array of flat bars, compared to the simple, bi-polar configuration. Such an arrangement is free of charge in the case that several conductors per polarity are anyway used for cooling or for other reasons. The simplest configuration of this kind is obtained with two return bars around a single central bar. Fig. 2 presents the calculated field picture of this split-field arrangement. The leakage field is larger in case of circular bars as the degree of confinement is less. However, the far field at one meter distance is only marginally affected by the geometry of the bars. The corresponding reduction of the far field, obtained by field splitting, is less important (a factor of 10) in case of bars of circular cross section. Evidently, the principle of field splitting can be extended by further division; the additional gain, however, is less and the practical complications increase rapidly. Consequently, the arrangement, chosen for the new Standards laboratory, consists of four central, flat copper bars of one polarity, mounted on the edge, surrounded by 2 x 2 identical bars of the other polarity.

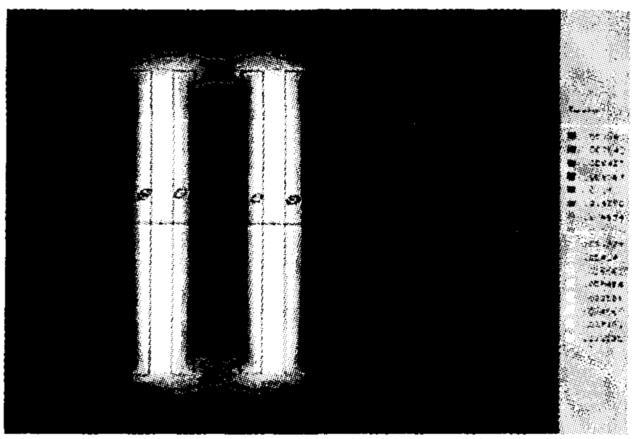

Figure 2a. Field from split-field bus bar configuration

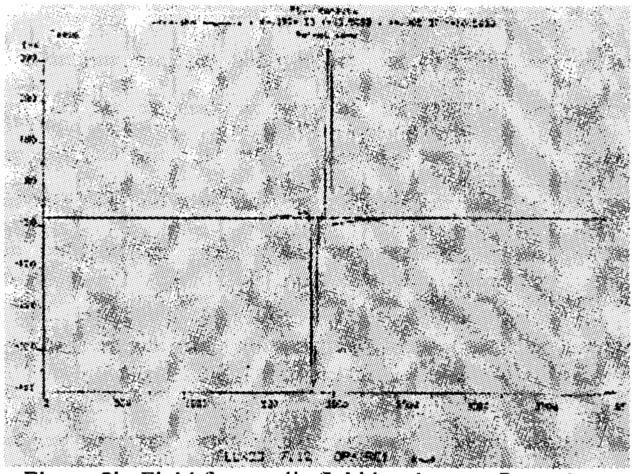

Figure 2b. Field from split-field bus bar configuration.

The busway was dimensioned for a maximum temperature rise of 40 K at a total current of 13 kA and a rise of 60 K at 20 kA. Taking into account a packing factor of 0.70 of the arrangement (1.5 mm interspacing of the 8 bars) and an emissivity of 0.9, obtained by coating with a matt black finish, calculations give the appropriate bar dimensions of 200 x 15 mm. The Lorentz force at 5 kA per bar is 18.2 daN per meter length. All supports, when not insulating, are made from non ferro-magnetic material.

The additional resistance across the bolted bus bar joints was minimised by silver coating of the contact surfaces and by applying adequate contact pressure distributed over an adequate number of bolts (according to DIN 43671). In this way it is even possible to achieve a transition resistance across the joints, which is inferior to the resistance of an identical length of the single bar as the double cross section at the joint more than compensates for the additional contact resistance. By introduction into the busway of flexible links (laminated segments) at appropriate locations, no mechanical forces will act on the joints. These measures will limit the formation of oxide on the contact surfaces, and the likelihood of an associated thermal runaway (ref. 2)

1.3 The Cells

For the design of the regulation, reference and measuring cells the quasi-coaxial configuration is obtained by division of the return conductors into eight, flat bars, symmetrically arranged around the transducer coil. Fig. 3 presents the calculated field picture in the regulation cell (700 mm diameter) and the field variation around the central perimeter of a typical transducer coil. In spite of the short distance between the DCCT coil and the return bars (70 mm) the field variation is only 1.6 $mT_{peak\text{-}peak}$. By increasing the cell diameter to 1000 mm the variation is reduced to 0.3 $mT_{peak\text{-}peak}$. This value was the design figure for the reference and measuring cells. A simpler configuration (4- or 2- fold symmetry) would have been satisfactory for a correspondingly larger cell diameter.

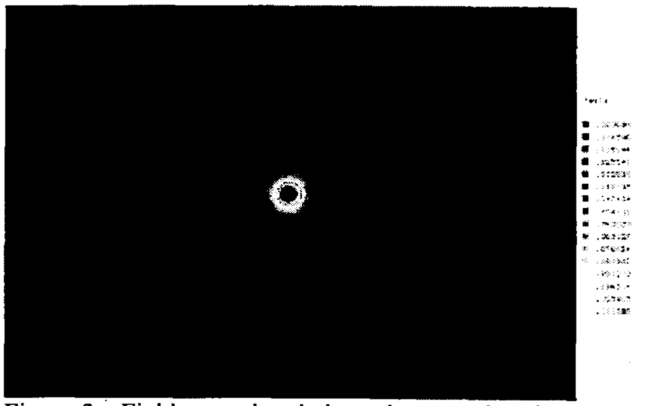

Figure 3a. Field around and along the central perimeter of a 20 kA transducer coil.

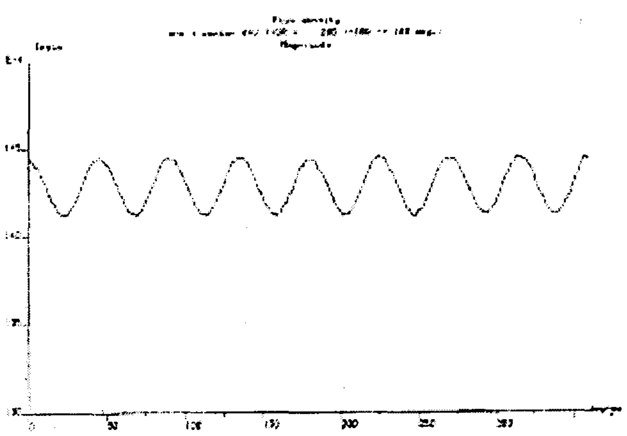

Figure 3b. Field around and along the central perimeter of a 20 kA transducer coil.

The measuring cell was designed for determination of the relevant sensitivity characteristics of each make and type of high-current transducer to be installed in the LHC. This cell is installed on top of, and electrically connected in series with, the reference cell. The electrical design was assisted by the program 'CASTEM' for calculation of the current densities of the various elements. The five metre high and heavy assembly is supported by a rigid stainless steel frame (fig. 1). For the loading and unloading of the heavy toroidal DCCT coils, both the central bar and the eight return conductors are disconnected and lifted 700 mm above the central conductor of the reference cell and the base plate of the measuring cell. A built-in, motor-driven screw is used for the lifting and a set of twelve pneumatic clamps of four different types (developed by 'Multi-Contact') ensure the automatic, high-current connections. The jaws of the clamps contain strips of special stainless steel contacts (lamellas) with silver-plated copper tips, capable of transferring 44 A per contact without water-cooling. The contact pressure is maintained by spring washers. Opening is provided by sets of pneumatic cylinders (3 kN per cylinder at 6 bars of air pressure). The contact surfaces are hard Nickel-plated. All the moving parts of the cell are fixed to a slide, mounted on two vertical shafts with bearings. The complete cell was built by Erico (D). The demand in terms of mechanical precision of this elevator is significant: 0.2 mm deflection at the top of the cell. The vertical translation speed is 7 mm/s. The water cooling circuits remain connected during these operations. The DCCT coils, to be mounted on the central conductor, are lifted into place by a hydraulic fork-lift.

An additional set of return bars with an off-centred middle part, will allow sensitivity studies with three different cell diameters. Special, insulating sleevings can be installed in the eight automatic clamps of the base plate in order to avoid conduction in the corresponding return bar, providing a convenient way to obtain a different configuration of the return current (4- and 2-fold symmetry). Two return bars are foreseen for water-cooling in case of 10 kA loading.

2. COMMISSIONING

Following completion of the control, surveillance and interlock systems, the complete facility was commissioned at 20 kA (September 1997). The total ohmic resistance was measured to be 95 $\mu\Omega$, giving a total power loss of 38 kW, slightly less than estimated. From measurements of the insulation resistance to ground at 500 V, the leakage current at 6 V (max. output voltage of the converter) is estimated to be 15 μA (10^{-9}). The electromagnetic field distribution inside the measuring cell at 20 kA was measured with a Hall effect Tesla-meter without the presence of transducer coils. Full agreement was found with the calculated picture obtained by calculation (fig. 3), indicating a good distribution of the return currents between the eight outer bars. A temperature stability test at 20 kA completed the commissioning. Temperature stabilisation of the air-cooled components was obtained after approximately 4 hours. A thermograph scan revealed the hot spots of the facility (ref. 3). As expected, the hottest point was at the top of the vertical bars, as the cooling conditions are less favourable here.

3. CONCLUSION

The upgraded current Standards laboratory fully meets the specifications and requirements. The complete installation is now ready to receive the first of a high number of transducers to be evaluated and calibrated for the LHC machine and its experimental areas.

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