THE SPLIT FIELD MAGNET OF THE CERN INTERSECTING STORAGE RINGS

J. Billan, R. Perin, V. Sergo
CERN, Geneva, Switzerland

Abstract

The Split Field Magnet, presently under erection at CERN, is a general purpose system providing a magnetic field volume of 28 m^3 for the analysis of the products of proton-proton collisions in the ISR.

The large size and power and the uncommon shape required special mechanical and electrical engineering solutions. A unique problem of beam optics and magnetic field shaping arises from the fact that the magnet is placed on an intersection of the ISR, with both proton beams crossing its field through about 11 m of length. The bending action is compensated by two additional magnets per beam : a small high field window-frame magnet placed upstream of the intersection and a large H-type magnet with asymmetric return yokes placed downstream. The strong focusing effects (about 2.4 T of integrated field gradient) occurring to the incoming beams at the edge of the magnet and at the junction of the two magnet halves, are suppressed or compensated by passive beam channels which can be adjusted to all working conditions of the magnet.

1. Introduction

One of the beam crossing regions of the CERN Intersecting Storage Rings will be equipped with a large magnet system, as the main component of a general purpose facility for measuring momenta and emission angles of particles generated by proton-proton collisions in a solid angle close to 4 π. From the point of view of particle analysis, the ideal instrument would be a magnet providing a large volume of intense and uniform field all over the intersection region and extending, free from any obstructions, to the entire space available

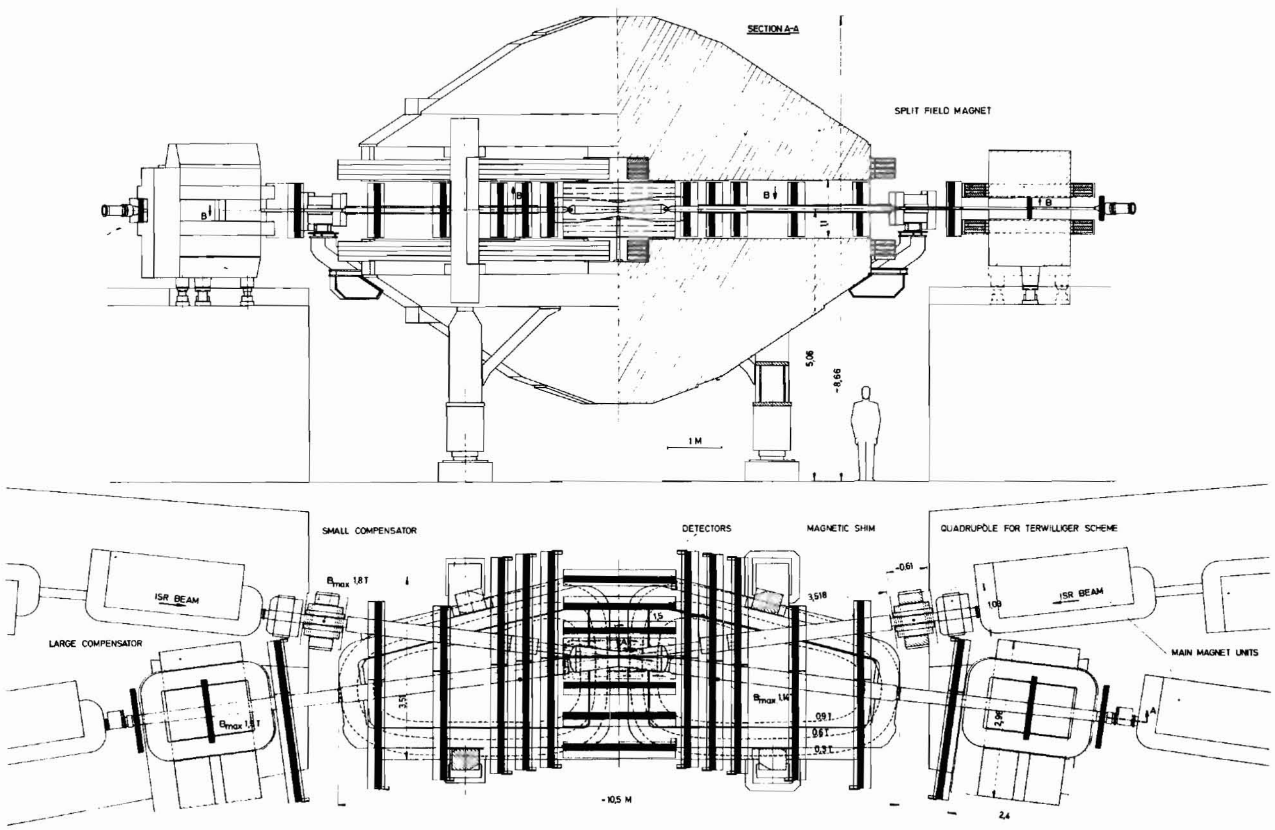

Fig. 1. Schematic layout of the Split Field Magnet facility on the Intersection region I-4. The multiwire proportional chambers, employed for the detection of the collision products, are also outlined.

between the ISR magnets on either side of the crossing point. However, a magnetic field system working on the circulating beam must restore the protons closed orbit with the correct angle and position at its end. This requires that the beam is bent in opposite directions and at least three regions with alternate magnetic fields. Among a number of possible solutions, a magnetic system providing zero field at the beams crossing point and fields of opposite signs upstream and downstream of that point, respectively, was adopted in spring 1969. The ISR Magnet Group was entrusted with the realization of the project and produced a practical design called the Split Field Magnet (SFM)[1].

A general layout of the system is shown in Fig. 1. The distinctive shape of the main magnet resulted from a compromise between the conflicting requirements of assuring the largest possible acceptance for secondary particles, while maintaining within reasonable limits the disturbance to the ISR beams and the financial implications of the project.

Each proton beam passes successively through an upstream compensator magnet, the two parts of the main magnet with vertical field component in opposite directions and a downstream compensator magnet. This last magnet will also be used as an analyzer for high energy particles produced at small angles and was, therefore, designed with a large air gap.

In order to protect the beams from the edge gradient effects where they enter the SFM, the vacuum pipes are in these regions surrounded by magnetic channels.

The trajectories of the ISR beams central orbits through the system in a typical operating condition are shown in Fig. 2.

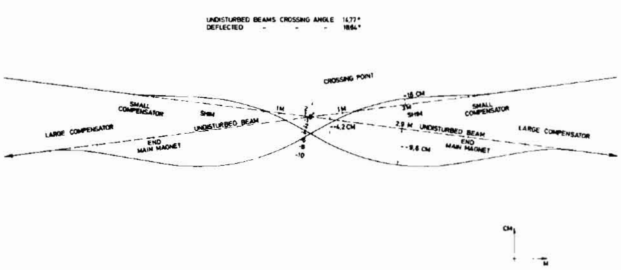

Fig. 2. Displacement of the ISR central orbits in the SFM at p = 25 GeV/c and B_o = 1.14 T.

To obtain a high transparency for secondary particles, the ISR vacuum chamber is in this region of special shape and with thin corrugated walls. It will be suspended from the magnet poles by means of carbon fiber epoxy impregnated rods and of thin metallic wires.

The SFM and the downstream compensator will be filled with particle detectors, most of them multi-wire proportional chambers for a total of more than 50 000 wires[2]. The trajectories of secondary particles can be geometrically reconstructed if they pass through at least three chambers or through a minimum of two chambers if the interaction vertex can be located. The knowledge of the magnetic field along the path permits the determination of the particle momentum. Figure 3 shows the field distribution in the median plane of the magnet and, for a number of momenta, trajectories of secondary particles produced in the intersection and having no vertical velocity component.

The SFM core has been manufactured by the firm Creusot-Loire, Paris, in their factory of Le Creusot, France. The excitation windings with their electrical and hydraulic distribution systems by Société Oerlikon, Paris, in their factory of Ornans, France, under the responsibility of Brown-Boveri & Co., Zurich. The large compensator magnets were manufactured by Société Alsthom, Belfort (France) and the small compensators by Société Oerlikon, Ornans.

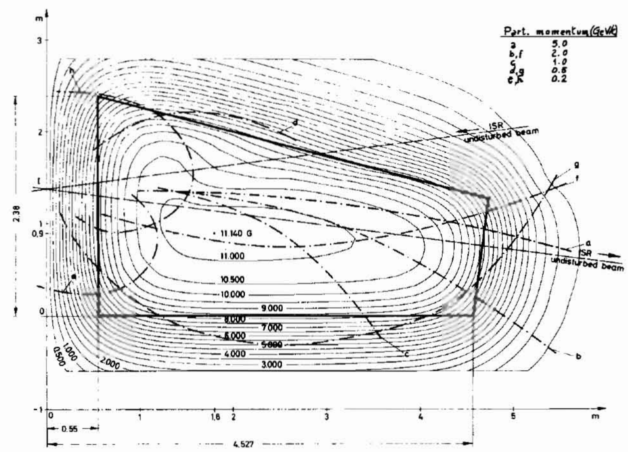

Fig. 3. Field map in the SFM median plane with typical tracks of pions of different energy, produced at the intersection point.

2. Main features of the SFM

2.1 General Description

The SFM (Fig. 1) can be regarded as composed of two horseshoe type magnets placed at equal distance on either side of a horizontal symmetry plane. The yokes, provided each with two excitation windings, are the mirror image of each other and consist of two parts symmetrically located with respect to the central vertical plane. When the magnet will be installed in the experimental Hall I4 of the ISR, this plane will coincide with the vertical radial plane of the ISR at the beams intersection.

The magnetic flux crosses the air gap twice, upwards in the left part and downwards in the right half of the magnet, respectively. The magnetic attraction between the yokes and the weight of the top yoke and coils are supported by four non-magnetic pillars. The possibility of separating the magnet into two halves along the vertical symmetry plane, for a second generation of experiments, has been retained by building the majority of the core components in two separate halves. Two smaller auxiliary pillars can replace one of the present pillars in each half magnet, thus forming a 3 point support.

Table I summarizes the main features of the SFM.

TABLE I

- Useful magnetic field volume	(m^3)	28
- Nominal max. induction in median plane	(T)	1.14
- Gap height	(m)	1.100
- Length of magnet	(m)	10.5
- Width of magnet	(m)	2.0 at the ends 3.5 at the centre
- Overall height	(m)	7.2
- Number of coils		4
- Current	(A)	6250
- Voltage	(V)	650
- Stored energy	(MJ)	16
- Total steel weight	(t)	840
- Total copper weight	(t)	42

2.2 The core

The yokes. The yokes were subdivided into pieces taking into account the mechanical stability of the structure, simplicity of machining and of handling. The maximum weight of any individual piece was limited to 60 tons, which correspond to the maximum crane capacity in the assembly and experimental halls.

The main components of a yoke (Fig. 4) are :

- 2 poles,
- 2 intermediate plates,
- 2 central blocks,
- 1 front side plate,
- 1 back tapered side plate.

From the structural point of view, each yoke is composed of two parts, each the mirror image of the other with respect to the vertical plane of symmetry. They are joined together by the clamps and by the side plates. The system of the two

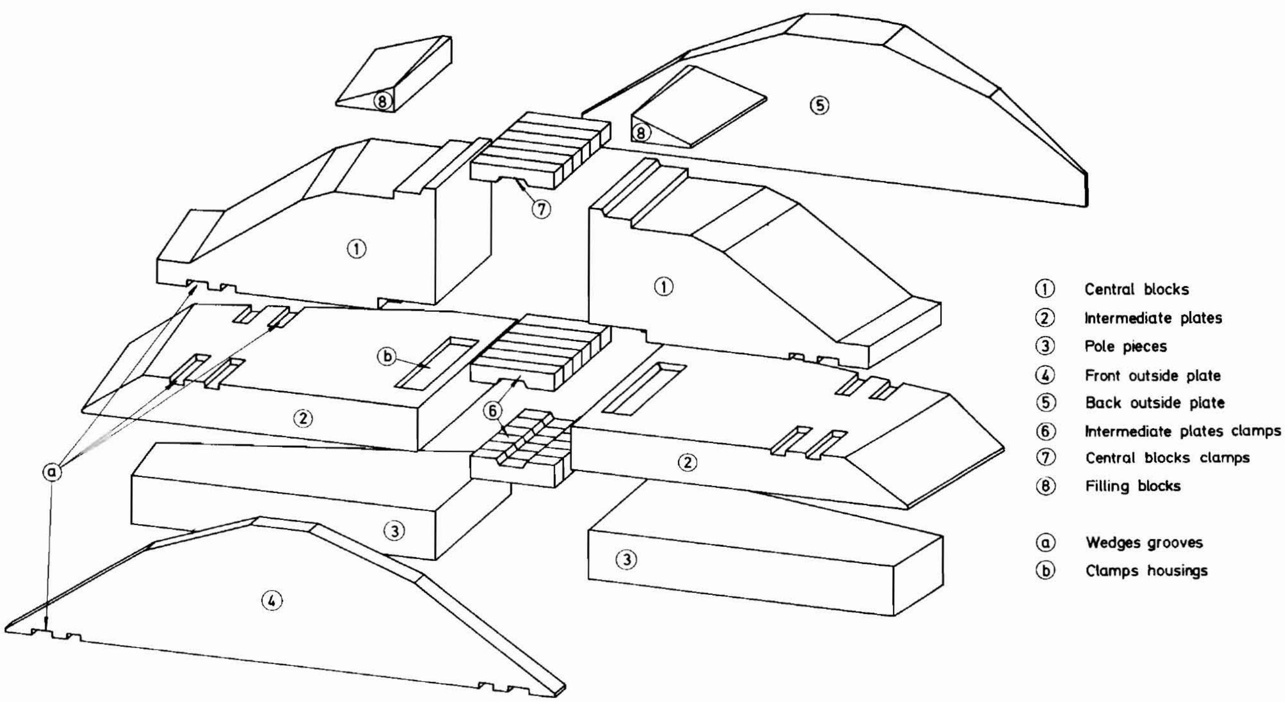

Fig. 4. Exploded view of the main components of the SFM upper yoke.

intermediate plates with their double row of clamps forms the main supporting beam of the whole structure. It is stiffened by the central blocks with their clamps and by the side plates. Each intermediate plate is additionally reinforced by the polepiece. Figure 6 shows one of the plates during assembly. One can recognize the slots for the wedges that transfer the longitudinal shear from the intermediate plate to the central block and to the front side plate.

All main components of the core, with the exception of the pole pieces, were cast from low carbon steel. The four polepieces were obtained from two forgings of an initial weight of about 150 tons each.

The above-mentioned main components of a yoke are fastened together by means of binding elements that can be grouped into a vertical and a horizontal system.

The vertical system consist of studs, that hold together the poles, the intermediate plates and the central blocks, and of bolts connecting the side plates to the intermediate plate. Figure 5 shows one of the bottom poles with the studs already inserted.

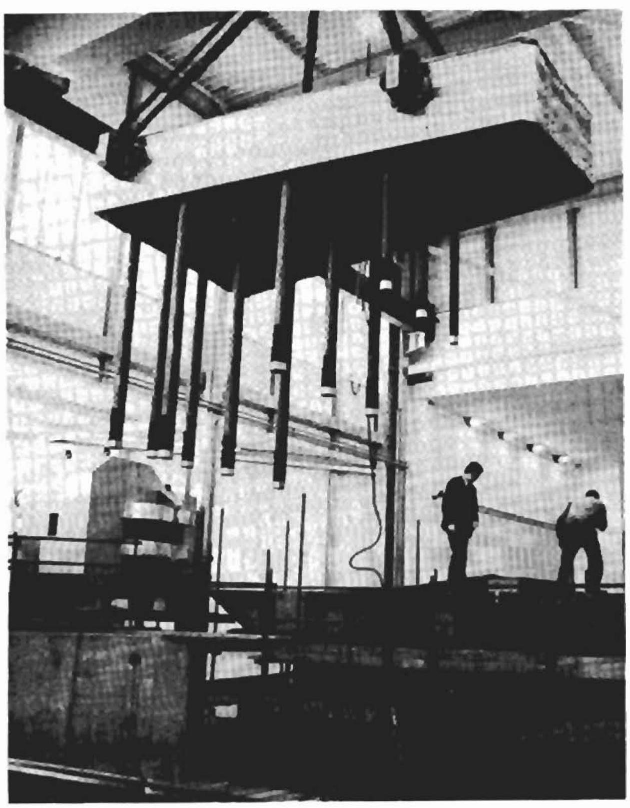

Fig. 5. A polepiece, provided with vertical through bolts, ready to be lowered in place. One of the large compensators can be seen on the left.

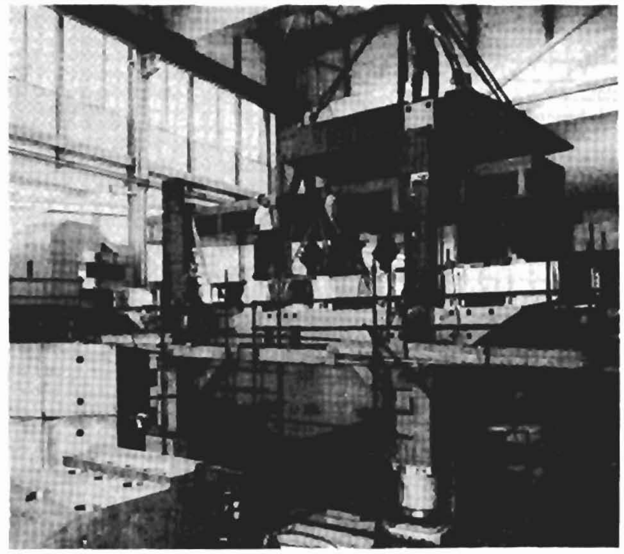

Fig. 6. Swinging into place of an upper intermediate plate.

The horizontal system includes :

- three rows of six clamps each along the vertical symmetry plane of the magnet,
- a set of shear wedges between the intermediate plates and the central blocks and the front side plate,
- a set of bolts fastening the side plates to the central blocks.

The pillars. Besides carrying the magnetic forces and the weight of the top part of the magnet (amounting to a total of more than 1600 tons), the pillars have to withstand also considerable lateral forces during the transport of the magnet and in case of earthquake.

Number, position and cross-sectional areas of the pillars were determined as a compromise between the conflicting requirements of limiting to a minimum the material obstructions to the interaction products escaping from the gap region and of providing sufficient stability. They have been made from austenitic steel having a high content of manganese (18.5 %). This material, which, from the point of view of magnetic properties, is as good as the best austenitic stainless steels, presents much better mechanical properties and is considerably cheaper. However, it is difficult to machine because of its hardness and very high resilience.

Mechanical design criteria. The shape and the dimensions of the SFM imposed detailed studies of the field patterns and of the stresses and deflections in each part of the structure.

Firstly, magnetic field computations were carried out by means of the MARE[3] program and, after the basic features of the magnet had been established, a 1:5 scale operative SFM model was built at CERN and employed for further studies. As an example, Fig. 7 shows the magnetic pressure distribution along the longitudinal symmetry axis of the pole as computed with the program and as resulting from field measurements in the model.

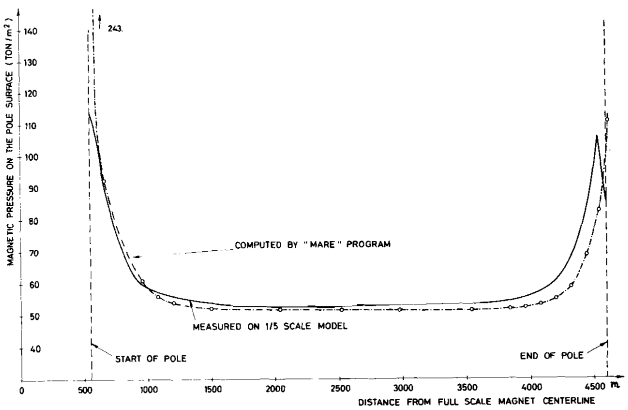

Fig. 7. Magnetic pressure along the longitudinal axis of the poleface.

For the intermediate plates, the first approximation calculation as a simply supported plate was implemented by the application of the finite element method[4] for which specific computer programs were elaborated.

The clamps were designed in such a way as to achieve the best possible continuity between the connected elements. They are tapered to avoid too high precision fitting of parts and the taper angle has been optimized at 23 ^{o} to minimize the stresses in them. Sets of six clamps were chosen instead of one long element only because of their better load sharing capacity. The tolerances on a single long clamp would have had to be too tight in order to ensure the required even load distribution.

In each yoke, the intermediate plates are locked to the central blocks by means of two rows of wedges as in a two slabs beam. Calculation of the pre-stressing forces on the wedges have been performed with the aim to obtain equal maximum stresses in the intermediate plates and the central blocks.

A carefully studied procedure was followed in the assembly of the magnet. As an example, one of the problems was to achieve an even load repartition among the 4 pillars. Of course the system is statically over-determined and therefore the share of the total load which is taken by a pillar depends on the actual dimensions, the stiffness and the relative positions of the components of the yoke-pillars system (an overload of 160 tons on a pillar produces only a 0.1 mm reduction in its length). In these conditions and considering the large size of the pieces and the practical assembly tolerances, it was hopeless to use any other method than shimming on the pillar support areas. This was made in two steps. Firstly by a geometrical survey of the gap between pillars and top intermediate plate, and then by successive trials with different shim thicknesses, checking the load repartition by means of strain gauges glued to the pillars faces. For these adjustments the upper yoke wholly assembled was lifted and lowered on the pillars by means of a set of hydraulic jacks resting on the bottom poles. Five of these jacks can be seen in Fig. 6, showing the mounting of the right upper intermediate plate.

2.3 The excitation windings

The four excitation windings, consisting each of four double pancakes, are of classical construction. The interturn insulation was wound with glass and glass-mica tapes and the pancake insulation with glass and polyester tapes. The whole was impregnated under vacuum with an epoxy resin. The electrical and water connections have been obtained as built-in parts of the pancakes with no conductor length protruding out, thus avoiding weak points in the insulation.

The windings are connected in series and excited with direct current from a stabilized power supply. Demineralized water, circulating inside the hollow copper conductor, keeps the upper temperature limit of the coils below 60 ^{o}C for a maximum water inlet temperature of 30 ^{o}C.

The size and weight of the coils and the limited clearance imposed between them and the polepieces lead to the design of a special lifting tool, which permits also to install and remove the coils without dismantling the upper yoke (Fig. 8)

The water cooled bus-bars are made from the same conductor as used for winding the coils. They are lodged inside a "C" shaped aluminium alloy profile. The residual spaces in the profile are filled with cast charged epoxy resin so as to form a strong monolithic structure.

3. Supports and transport system

The complete magnet rests on three adjustable jacks of 500 ton capacity by means of two intermediate transverse "U" shaped supports of welded steel plate.

These jacks, which can be actuated manually or by means of an electro-hydraulic group, have a vertical stroke of 200 mm. The foot of the vertical piston is spherical and sits in an equally

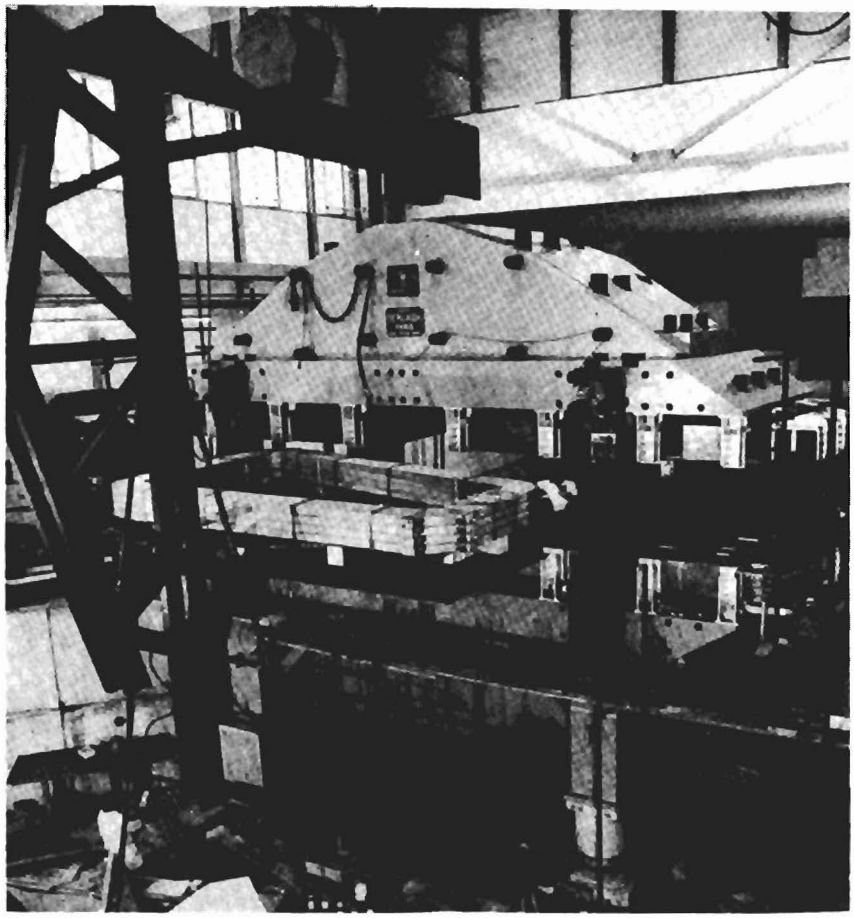

Fig. 8. An upper coil being mounted by means of the water-ballasted lifting tool.

shaped concavity of a sledge, which can be displaced horizontally by ± 75 mm in two perpendicular directions by means of two coupled small pistons. The jacks allow to adjust the position of the complete magnet with an accuracy better than 0.1 mm.

In order not to interfere with the ISR operation, the magnet is being assembled in a hall contiguous the experimental hall I4. Three bogie carriages running on 16 rails will be used for its transport from the assembly hall to the experimental hall. One central 4-bogie carriage will be fixed under the lower yoke and the two side carriages under the "U" shaped supports at the place of the jacks. The side carriages are provided with 6 bogies each. A system of 16 jacks (one for each bogie), which are pipe-connected and equipped with hydraulic accumulators, shares evenly the weight of the magnet during transport. The whole equipment will be moved by two pulling jacks which will be hooked to strong points fixed between the rails.

4. Interrelation with the ISR. The compensators and the magnetic beam channels

4.1 Influence of the SFM on the ISR machine

The SFM may cause several kinds of disturbance to the circulating beams.

The most obvious effect of the SFM is due to the dipole component of its magnetic field, which modifies the trajectories of the beams. With the two compensators, the distortions do not propagate outside the SFM zone, but in this zone the crossing angle of the beams is modified (see Fig. 2). The original crossing angle of $14.77\,^{\circ}$ is increased to $18.6\,^{\circ}$ and consequently, the interaction rate N_{IR} diminishes as follows :

$$N_{IR} = N_{IR_o} \cdot \frac{\mathrm{tg}\ 7.4\,^{\circ}}{\mathrm{tg}\ 9.3\,^{\circ}} = 0.79\ N_{IR_o}$$

The disturbances due to the other components of the SFM field are more troublesome because they affect all of the ISR intersections. An uncompensated large focusing effect produced by the localised quadrupolar component would blow up the beams. In fact, as shown in Fig. 9, two zones of variable field are traversed by the beams with an angle different from 90 °. The first zone is at the entry of the beams in the SFM where the angle of the beam with respect to the pole edge is about 20 ° and the second zone is at the inversion of the field in the centre of the SFM where the incidence angle of the beam is about 80 °. In these zones, the integrals of the gradient along the beam line reach respectively 2 T and 0.3 T at maximum field. This gradient reduces the energy spread of the particles which can be stacked in the ISR and increases the transverse dimensions of the beam. These two effects reduce the maximum beam current and increase the beam height at the intersection, thus causing a drop in the interaction rate.

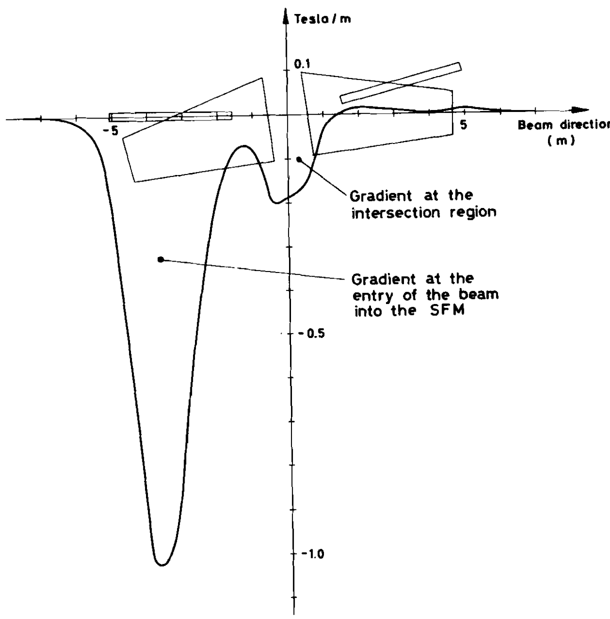

Fig. 9. Transverse gradient without magnetic beam channels at maximum field level.

Magnetic beam channels described in section 4.3 protect the beams from these focusing effects. With these devices, as shown in Fig. 10, the first peak of gradient is almost cancelled out at maximum field level and slightly overcompensated at half field level. The gradient in the intersection region cannot be cancelled out directly, but is compensated by an equivalent zone of gradient of opposite sign produced by the moving part of the beam channels at an average distance of 1.75 m from the SFM centre. This compensation reduces the drop of the interaction rate due to the gradient at the intersection region from 25 % to less than 10 %. At half field level, the magnetic beam channels are not saturated and the overcompensation which results, is used to counterbalance the gradient in the intersection region without the need to produce gradient with the moving part of the beam channels. However, this compensation, being centered at about 3 m from the field inversion plane, is slightly less efficient (approximately 15 % instead of 10 % loss of interaction rate).

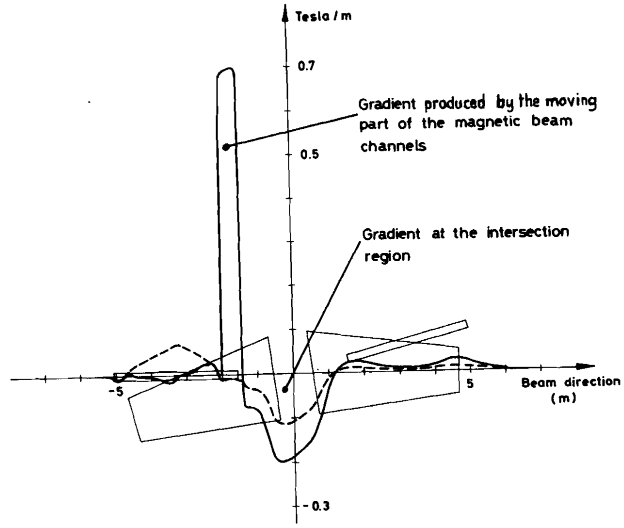

Fig. 10. Transverse gradient with magnetic beam channels at :
- maximum field level (————)
- half field level (--------)

Field components of higher order (sextupolar, octupolar, etc.) may excite resonances and increase the decay rate of the beams. Resonances of any order may in fact be produced since the perturbations are localised and do not respect the periodicity of the ISR machine. A local correction can be achieved by means of auxiliary windings inside the magnetic beam channels. Furthermore, a system of sextupole and octupole magnets has been designed in order to compensate 3rd and 4th order resonances, respectively, arising in any point of the ISR machine.

4.2 The Compensators

The Large Compensator Magnets. These magnets are used both for compensating downstream the bending effect of the SFM on the ISR beams and for the analysis of secondary particles of large momentum produced at small angles. They are H-type magnets in which one leg had to be made much thinner than the other because of space limitations. In spite of this basic asymmetry, it was possible to shape the core in such a way that the magnetic field distribution in the central part of the air gap remains practically symmetric at all field levels. The core shape studies were carried out by means of the program MARE.

A 200 x 400 mm^2 window in the main return yoke permits side access to the centre of the gap for the location of experimental equipment. The core is made of a number of steel pieces which are bolted together. The two water cooled excitation windings, one around each pole, consist of four coils in the form of double pancakes.

The Small Compensator Magnets. These magnets, of the window-frame type, are placed upstream of the SFM and pre-compensate its bending effect on the ISR beams.

The core consists of two equal halves, each made from steel plates, fastened by means of welded tensions straps. Each winding consists of three saddle shaped coils having the form of double pancakes.

Table II summarizes the main characteristics of the two types of compensators.

4.3 The magnetic beam channels

Besides the suppression of the entry gradient, a certain number of other criteria were taken as guidelines to define the magnetic channels.

- Dimensions. The magnetic channels should be as close as possible to the vacuum chamber in order to reduce the minimum obstructed solid angle as seen from the intersection; for the same reason, they should be as far as possible from this intersection.
- The field level in the magnetic channels should not be more than 90 % of the field level in their absence, in order not to overload the Small Compensators.
- The system must function at all operating conditions foreseen for the SFM, i.e. between 25 % and 100 % of maximum excitation current.

TABLE II

Model denomination		Large Compensator		Small Compensator
Type of magnet		H - shaped		window-frame
Position with respect to the intersection point		downstream		upstream
Number of magnets		2		2
Nominal induction	(T)	1.5		1.8
Gap height	(mm)	400		75
Steel length	(mm)	1500		435
Pole width	(mm)	800 950	tip root	350 380
Overall width	(mm)	2980		1030
Current	(A)	2060		1050
Voltage	(V)	152		44
Total weight	(kg)	69'000		2'050

Different solutions have been envisaged. Superconducting solenoid pipes surrounding the beams have been discarded because of the excessive dimensions of the cryostat and of the high cost of the system. Correcting currents have been eliminated because of the high currents necessary and as a consequence, the large resulting dimensions. A quadrupole magnet placed nearby the Small Compensator magnet would not provide sufficient correction because of the too large distance from the region of the gradient to be compensated. The adopted solution was that of a passive system: the form itself of the magnetic parts employed causes the suppression of the gradient. This solution has been studied

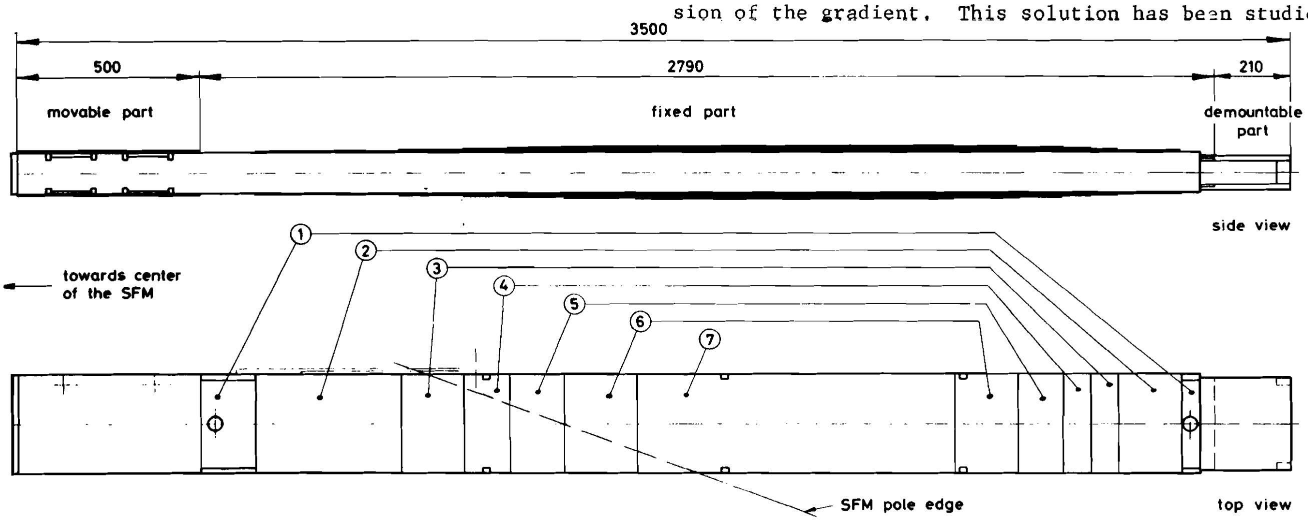

Fig. 11. Magnetic beam channel - Longitudinal views.

and tested in the 1/5 scale model of the SFM.

The magnetic beam channels have the form of long rectangular tubes of variable section. One can distinguish in them two main parts (Fig. 11).

Fixed part. This part surrounds the vacuum chamber over a length of 3 m in the entry region of the beam in the SFM. Figure 12 shows the larger cross section (zone 7) which is in the region of maximum gradient. This section is variable according to the level of field gradient to be corrected. Zones 1 are only made of two horizontal plates and two walls of low carbon steel. In these zones, the gradient to be corrected is weak and the thickness of the horizontal plates is sufficient to make the field uniform inside the magnetic channels. The magnetic action of the walls is essentially to limit the integrated field on the beam trajectory. In zones 2, an angular shaped piece is placed on the top and the bottom of the horizontal plates. The field inside the beam channel is made uniform by means of the variable reluctance produced by this system. Zones 3 to 7 have an increasing number of 1.5 mm thick steel sheets superimposed on the system of zone 3 to reinforce its action. The end of the magnetic beam channels does not have any walls and the horizontal plates are demountable. This has been done to provide lateral access to the vacuum chamber for an ion pump, which has to be as close as possible to the intersection region, and to allow access for welding and cutting of the chamber.

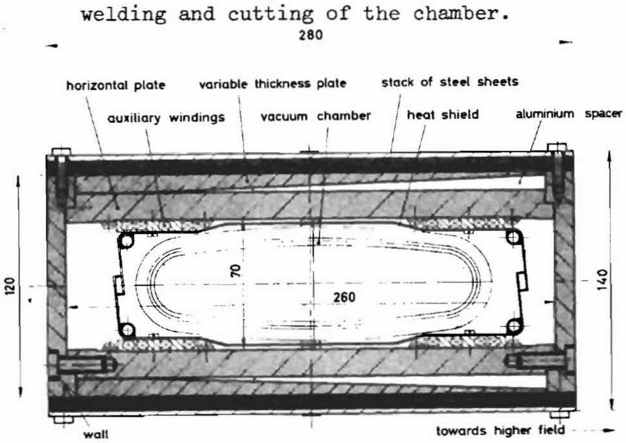

Fig. 12. Cross-section of the fixed part of a magnetic beam channel.

Moving part (Figs. 13 & 14). Over 500 mm, at the end nearer to the centre of the SFM, the two horizontal plates can be inclined up to approximately 2°. The gradient obtained in this way allows to compensate that of the intersection region and permits to optimize the magnetic channels behaviour at all field levels (see Fig. 10). The mechanism is actuated by a hydraulic jack, through a rack and pinion system. The opening of the plates is monitored by a linear potentiometer. The overall angular accuracy of the opening of the plates is better than 0.3 mrad, which corresponds to less than 1 % of the gradient given by the system.

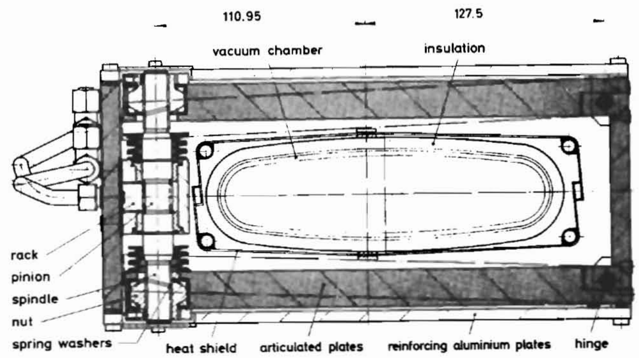

Fig. 14. Cross-section of the moving part of a magnetic beam channel.

The expected field distribution in the different parts of the magnetic beam channels is shown in Fig. 15.

5. Present state and project completion

The compensator magnets are already tested and measured, while the assembly of the SFM is nearly completed.

The SFM will then be thoroughly tested under power; the mechanical and thermal stresses in the most critical components will be checked in static conditions and during transients by means of strain gauges, thermocouples and flux measuring coils.

Two series of magnetic measurements will follow. The first set of measurements, limited to the regions crossed by the ISR beams, will have the purpose of defining the proper setting of the compensators and of the magnetic beam channels for different operating conditions of the system. In

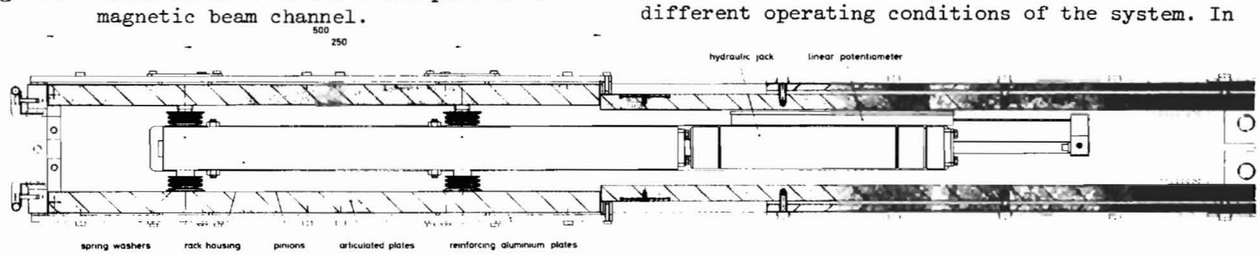

Fig. 13. Magnetic beam channel - Mechanism of the moving part.

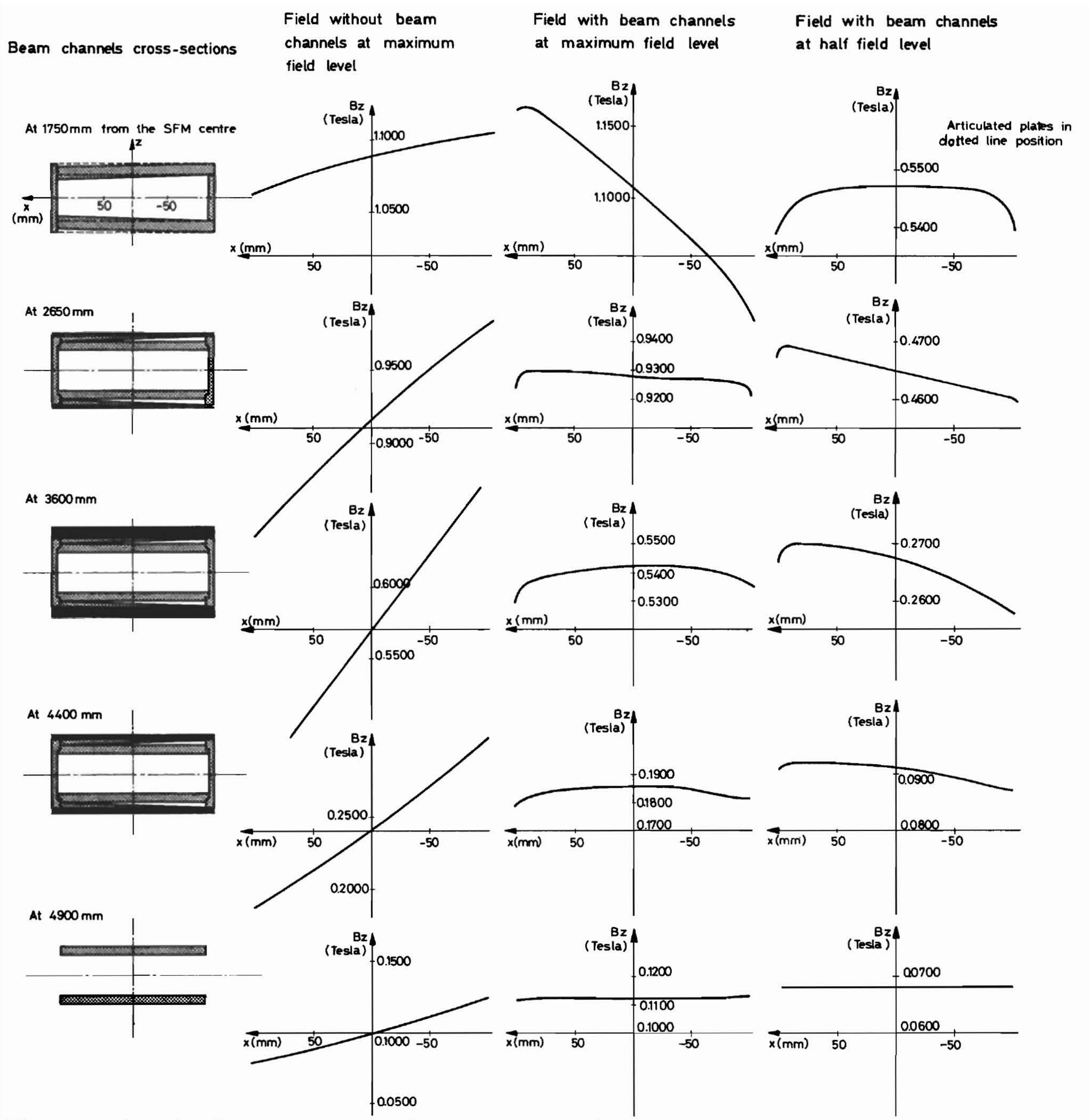

Fig. 15. Field in different cross sections of the magnetic beam channels.

the second series of measurements, the magnetic field will be mapped in the whole volume to be used for particle analysis and at different field levels. The magnetic measurements and the necessary special equipment are described in a separate paper[5].

The whole SFM system will be then transported into the ISR tunnel and installed in the intersection I4.

Acknowledgements

The SFM design has been a team work under the leadership of L. Resegotti. Besides the authors, the members of the team were : Ph. Bryant, S. Caeymaex, G. Carter, H. Grabner, J. Hirsbrunner, H. Horisberger, C. Mazeline, G. Pluym, M. Salmon, H. Stucki and K.E. Wright.

References

1. L. Resegotti, "Progress report on the Split Field Magnet for the ISR", CERN internal report ISR-MAG/69-58.

2. A. Minten, "The Split-Field Magnet Facility", CERN internal report SFMD Note 4, 28 April 1971.

3. R. Perin and S. Van der Meer, CERN 67-7, ISR Division (1967).

4. O.C. Zienkiewicz and Y.K. Cheung, The Finite Element Method in Structural and Continuum Mechanics (Mc Graw-Hill, London, 1967), p.p. 1-73.

5. J. Billan, J.P. Grillet, K.N. Henrichsen, F. Schäff, "Precise semi-automatic field mapping in the Split Field Magnet of the ISR", paper presented at this Conference.