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SEPTUM MAGNETS FOR THE EXTRACTION CHANNELS OF THE 400 GeV SPS

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Summary

For each of the two extraction channels of the CERN 400 GeV Super Proton Synchrotron (SPS), two types of one-turn septum magnet have been developed.Each channel contains 8 magnets of the type "Magnet Septum Thin (MST)" with a 4.2 mm thick copper septum and 10 magnets of the type "Magnet Septum Extractor (MSE)" with a 17 mm thick copper septum.All yokes have a length of 1.1 meters. The magnets are slowly pulsed with currents of respectively up to 7.5 kA and 24 kA, with rise and fall times which can be adjusted between 0.2 and 0.4 s. The main innovations in the design of the magnets are :

1) The copper septum is shifted partly outside the gap, provided with "shoulders" to diminish the stray field and fixed against the yoke of these "shoulders" with insulated aluminium clamps .
2) Elimination of any ceramic-metal connection for the insulation of the cooling water circuit inside the vacuum tank.
3) Utilisation of only radiation resistant insulation.
4) Magnet bakeout inside the vacuum tank.

A prototype of the thick septum magnet has been pulsed 5.4 x 10^6 times in the laboratory without any incident. So far, the first extraction channel has operated regularly since July, 1976, without any problems. After a bakeout at 100°C and 4 days of pumping, the vacuum in the septum magnet tanks is lower than 5.10^{-9} torr.

1. - Introduction

In high-energy particle accelerators septum magnets are generally used as a second stage of the extraction system, the first stage being a thin electrostatic septum [1]. The two extraction channels of the CERN 400 GeV accelerator eject the protons in the horizontal plane.Each of the channels consists of three sets of septa. The first set is composed of four vacuum tanks containing 4 electrostatic septa.Each septum is 3 m long and is made of 2000 wires of 0.12 mm diameter. The total deflection given by the set of electrostatic septa is 0.3 mrad. Thereafter, a set of four vacuum tanks, each containing two thin septum magnets MST provide a maximum total deflection of 3 mrad. This set of magnets is finally followed by an assembly of 5 vacuum tanks, each containing 2 thick septum magnets MSE. A total maximum deflection of 12 mrad is given to the 400 GeV protons by the MSE. Each of the three sets of septa is installed on a 15m long beam, the position of which is remotely adjustable with a precision of ± 0.05 mm. In this publication, only the septum magnets MST and MSE will be described.

The magnets are aligned so that their septa, serving as magnetic screens, are placed in the separation created by, respectively the electrostatic septa and the MST between the circulating and the extracted beam. Ideally, no proton of the circulating or extracted beam should hit the copper septum but in practice, the region of the magnets is strongly irradiated. The dose rate resulting from the unavoidable interactions of a small fraction of protons with the wires of the electrostatic septum is evaluated to be 3 * 10^9 rads/year on the copper septum and 10^8 rads/year on the back of the yoke, assuming an average beam intensity of 2.5 * 10^{12} protons/sec at 300 GeV and 4500 hours of yearly operation[2]. In addition, a possible halo of the beam, a bad adjustment of the accelerator or a fault of a magnetic element of the accelerator or the extraction systems may seriously increase the evaluated radiation dose. These considerations led to a design with a single turn coil, no insulation of the septum with respect to the yoke and a careful choice of electric insulators for the other parts of the magnets.

2. - Magnetic field

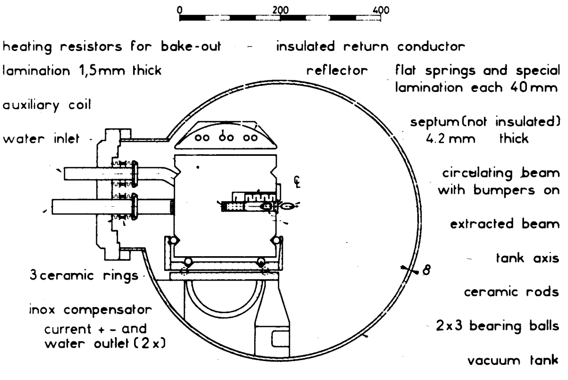

Fig. 1 Section of thin septum magnet (MST). For thick septum (MSE) only the coil is different (return and septum).

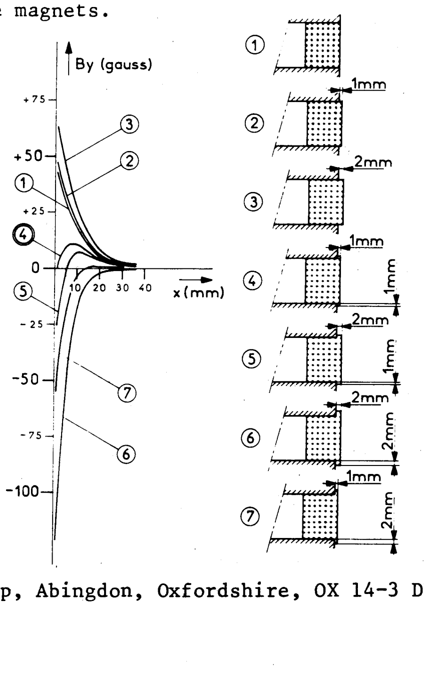

Fig.2 Calculated strayfield in the median plane of the MSE. Case 4 shows the septum geometry that has been chosen.

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The septum magnets described in this report produce a uniform magnetic field in the gap of a C-shaped yoke. The field is limited by the one-turn copper septum closing the gap as shown in Fig. 1.

The field outside the septum where the circulating beam passes is not exactly zero because of i) the finite permeability of the iron yoke, ii) the coercive field, iii) small clearances between the septum and the yoke that are unavoidable in spite of the absence of insulation, and iv) the channels for the cooling water in the septum.

The effect of the septum on the magnetic field has been calculated with the help of the 2-dimensional program MAGNET [3]. The rectangular shape of the ideal septum was modified as shown in Fig. 2 by adding an outer copper strip higher than the gap. In this way, two shoulders are created which have a minimizing effect on the fringe field. In addition, they permit the septum to be fixed against the yoke by means of 52 insulated clamps per yoke and to withstand the magnetic force of $2 * 10^4$ N for I = 24 kA and B = 1.5T. In the calculations the cross section of the yoke was increased until practically no further variation of the fringe field could be observed at I_{max} = 24 kA. In order to simplify the whole construction and to economize in tooling, the same lamination was chosen for the two types of magnet.

In addition to the numerical method, an analytic approach using conformal transformations[4] has been developed of which the results are in good agreement with those of the programme magnet. This method also allowed to evaluate the influence of the circular cooling channels in the septum (4 for MST, 16 for MSE) and good agreement with the corresponding measurements is obtained as shown in Fig. 3.

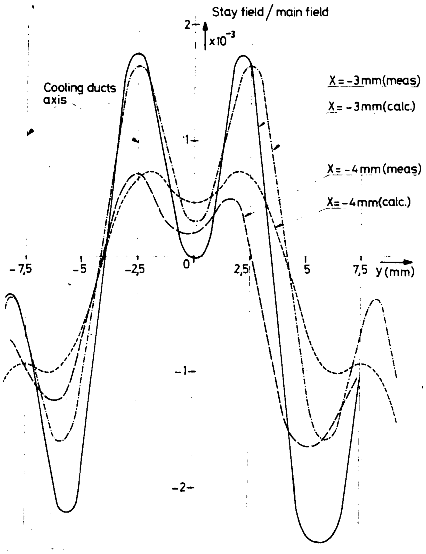

Fig.3 Vertical variation of the stray field B_y for a MST magnet, B_o = 0.38 T.

The magnets are pulsed to allow the extraction of beams at different energies during the same machine cycle. This also reduces the mean energy dissipated in the magnets and the size of their power supplies. Finally, it avoids the presence of the stray field during injection at 10 GeV/c. The specified cycle corresponds to a flat top at peak current of 1.4 sec. duration with rise and fall times of 0.3 sec. and with a repetition rate of 4 sec. This cycle requires that the yokes are laminated and careful allowance is made for the periodic expansions and constructions of the mechanical assembly. The yoke is composed of 670 laminations, each 1.5 mm thick. These laminations are oxidised by the blue steamed process and thereafter by heating them in air at 340°C for 4 hours which results in a surface resistance of the order of 1.5 $\Omega.cm^2$. Oxidation obtained by steam or in air only, yields hardly more than 0.1 $\Omega.cm^2$ or 0.2 to 0.3$\Omega.cm^2$ respectively.

The laminations are made of extra soft iron *) with less than 0.03% carbon and a coercive field $H_c \leq 0.55$ oersted. The time constant of eddy currents is 1.6 msec and is therefore negligible compared with the minimum risetime of 100 msec. The time constant of the 20 mm thick end plates is, however, of the order of 0.5 sec. It has been measured that these currents have an influence of less than 10^{-3} of the effective magnetic length even at the beginning of the flat top.

The laminations are assembled with four rods in the longitudinal direction of the magnets with a total force of $3.2 * 10^4$ N. The rods are mounted with insulating washers in order to avoid an induced current and to minimize the current in the yoke parallel with the current in the septum. In the case of the thick septum MSE, a set of mirror plates and intermediate connecting plates[5] strongly reduce the fringe field near the ends of the coil. As a result, the integrated stray field could be optimized for the whole range of septum currents as seen from Figs. 4 and 5.

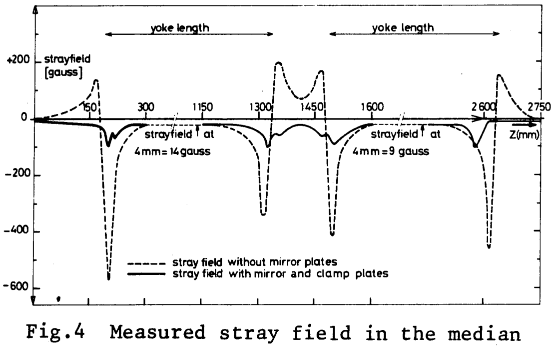

Fig.4 Measured stray field in the median plane at 4 mm from the septum of the prototype MSE for 25 kA.

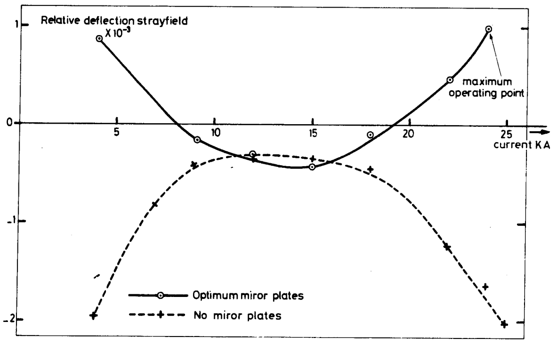

Fig.5 Relative deflections of the stray field in the median plate as a function of magnet current for the MSE at a distance of 4 mm from the septum.

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*) laminated iron Magnetil BC, Cockerill (B)

An auxiliary coil of a total of 18 mm^2 of copper placed behind the return of the main coil and around the back leg of the yoke, permits the compensation of the remanent field and its contribution to the stray field during the injection. The main parameters of the two types of magnet, which only differ in the ends of the yokes and in the coils, are summarized in Table I.

TABLE I

	MST	MSE
Lenth of yoke	1100 mm	
Height and width of yoke	256 mm x 252 mm	
Packing factor	0.95	
Gap height	20 mm	
Gap width (lamination)	134 mm	
Gap width (physical)	98 mm	62 mm
Septum thickness	4.2 mm	17 mm
Return coil cross section (w x h)	24mmx18mm	48mm x 18mm
Septum copper area	53 mm^2	215 mm^2
Return copper area	340 mm^2	680 mm^2
Weight of full tank with two septum magnets and support	2200 kg	2270 kg
Maximum field	0.471 T	1.508 T
Magnetic length (measured)	2247 mm	2237 mm
Radial homogeneity of deflection (measured)	$\leq 4.10^{-3}$	$\leq 2.10^{-3}$
Relative optimised stray field deflection (measured)	$\leq 1\text{-}3.10^{-3}$	$\leq 1\text{-}3.10^{-3}$

TABLE II

	MST	MSE
Coil resistance per tank (two magnets) after an assumed irradiation for 10 yrs.[6]	1.12 mΩ	0.36 mΩ
Series inductance of two magnets	16.2 µH	13.8 µH
Resistance of the septum (1.1 meter)	0.38 mΩ (35°C)	0.093 mΩ (32° C)
Peak current (I_o)	7.5kA	24kA
RMS current (I_{rms})*	4.875 kA	15.6 kA
Peak current density	141 A.mm^{-2}	112 A mm^{-2}
Current in correction coil	11 A	11 A
Pressure drop	17 bars	17 bars
Flow rate for two magnets	0.67 ℓs^{-1}	2 ℓs^{-1}
Water speed in the septum	14 ms $^{-1}$	10.2 ms^{-1}
Temperature rise of septum (average over the length)	18 °C	15 °C
Temperature rise of return conductor (average over the length)	21°C	21 °C

*) Flat top of 1.4 s, rise and fall time of .3s, repetition rate of 4 s, $I_{RMS} = 0.65\ I_o$.

3. - Septum Coils

As shown in Fig. 6 the full coil assembly consists of a septum, a return conductor, connection boxes, two cylindrical current supply conductors and an additional tube made of stainless steel which supplies the cooling water in the middle of the two circuits. A double coil is installed in 2 yokes each of 1.1 m length. This represents 2 magnets in one vacuum tank. The electric circuits of the 2 magnets are in series, the cooling circuits in parallel.

All these parts of the coil, with the exception of the stainless steel tube for the central water inlet, are entirely made of copper OFHC (less than 10 ppm of oxygen) which facilitates the brazing under vacuum and avoids the "hydrogen unsoundness". The latter is due to the recombination, under heat, of residual oxygen and hydrogen contained in the reducing atmosphere during the heat treatments for the drawing of the bars or the last brazing with a blow-torch resulting in the formation and propagation of microleaks in the body of the copper. The OFHC copper of the connection boxes must, moreover, be forged to avoid microcracks and microleaks. In fact, serious problems due to these two effects were encountered at the beginning of the series production of the coils.

The septa consists of rectangular bars of 3.6 mm * 5 mm for the MST and 4 mm * 5 mm for the MSE with circular cooling channels of 2.8 mm diameter. The return coils are made of bars of 6 mm * 6 mm with cooling channels of 3.8 mm diameter. The bars are brazed together under vacuum adding to the septa the additional copper strips of 0.6 mm for the MST and 1 mm for the MSE. Finally, the septa and return coils are brazed to the connection boxes with a blow-torch. Four types of brazing (Pd-Ag-Cu and Ag-Cu) with decreasing melting point were used for the successive brazing operations. The dimensions of the bars and tools for brazing under vacuum are such that it is now possible to avoid machining the septum height of 19.90 mm,the final dimension being obtained by simple slight squeezing. Electrical and hydraulic parameters are shown in Table II.

The insulated supply pipes for the cooling water are connected to the 3 feedthroughs of the coil assembly outside the vacuum tanks. This obviates problems linked with the use of ceramics or any other radiation resistant insulating material between a high vacuum of $5 * 10^{-9}$ torr, in the accelerator and a water pressure of 25 bars (absolute).

4.- Electric insulation

For the reasons given above we have chosen to construct a septum magnet with a single turn coil, without insulation from the yoke. This solution has the inconvenience that small parallel currents develop inside the laminations close to the regions of contact with the septum. Calculation[4] and measurement show that this parallel current is about 1% of the main current.

For the insulation of the return conductor and the auxiliary coil different materials were examined and tested, in particular for their mechanical properties and their resistance to abrasion as a function of their irradiation in a mixed neutron and gamma field at an experimental nuclear reactor. Finally a stratified glass-polyimide* (23% polyimide) was chosen which after irradiation at 10^{10} rads only shows a slight reduction of its mechanical properties [7].

Aluminium oxide was sprayed by gun on the surface of the clamps keeping the septum in place and on the extreme ends of the flat springs (Fig. 1) that push the return coil against the back of the gap. Aluminium oxide sprayed by plasma-gun and ground, was used for the insulation of the washers for the assembly rods of the yoke.

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*) Pyralin, Dupont de Nemours, Wilmington, Delaware, USA.

A composite material, glass-mica, was employed for the thick insulation pieces of the auxiliary coil on the outside of the yoke and also for the pieces used for retaining and centering the leakproof passage of the 3 feedthroughs, at the back of the yokes and outside the vacuum tank. The bus-bars supplying the magnets are insulated by means of thick plates made of a composite material asbestos-cement*)

Ceramic rings (95% aluminium oxide) between metallic compensating bellows form the vacuum tight wall at the level of the three current and water supply conductors and ensure the insulation of the coil with respect to ground. Cylindrical ceramic rods (95% aluminium oxide) are employed to support the yokes and to keep them in place on their supports as shown in Figs. 1 and 7.

5.- Thermal dilatation of the septum

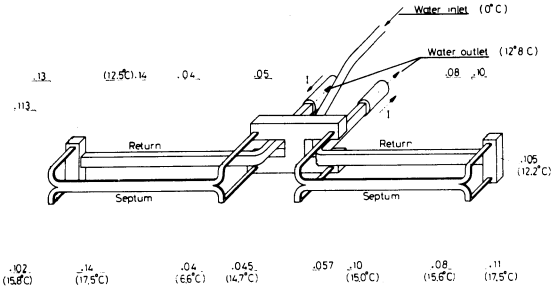

Fig. 6. Instantaneous expansions in mm, temperature rises of the copper in brackets, for the MST. All expansions are measured relative to the yoke; total flow rate 0.67 ℓ/s^{-1}, $\Delta p = 17$ bars, I = 6000 A.

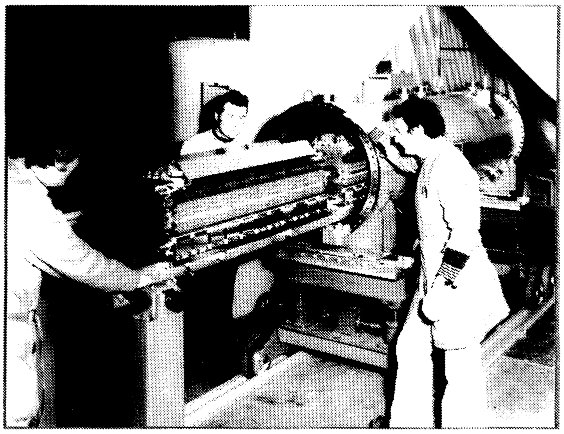

Fig. 7 Installation of two septum magnets MSE in their vacuum tank.

At each current pulse the septum grows longer by about 0.15 mm due to the heating of the copper (Fig. 6). A small clearance of 0.05 mm was left between the yoke and the pieces retaining the septum in order to facilitate this lengthening with minimum friction. The return part of the coil undergoes about the same lengthening since the water coming from the septum has already warmed up. This latter dilatation occurs in the presence of the combined pressure of the flat springs and the magnetic field and posed the problem of friction of the copper and its insulation on the backside of the magnet gap. This problem was solved by the insulating sheath made of the composite material glass-polyimide already mentioned above. Earlier tests with a simple sheath of glass tissue had led to its destruction after $2 * 10^5$ pulses compared to a desired lifetime of 10^7 pulses.

6. - Vacuum and bakeout

All components of the magnets and their supports were cleaned in an ultrasonic bath of alkaline solution and in vapour of perchlorethylene. Thereafter they were carefully assembled in a clean room. The bellows did not undergo an ultrasonic cleaning. The feedthroughs were leak tested after bakeout down to leak rates of 10^{-10} torr ℓ/sec. All joints used on the vacuum tanks are metallic. Moreover, the septum coils were leak tested piece by piece after each brazing operation, after the final assembly before and after bakeout at 100°C, and after more than $2 * 10^5$ pulses at nominal current and another moderate bakeout at 80°C.

Each set of two magnets with their support is installed in a vacuum tank of stainless steel as shown in Fig. 7. A bakeout of the yokes during 6 hours at 100 °C takes 4 days and permits to reach a vacuum of $5 * 10^{-9}$ torr by means of 2 ion pumps each with a pumping capacity of 400 ℓ/sec. The bakeout is done by means of heating resistors. These are mounted with a reflector on top of the yokes, of which the 1340 laminations represent the main source of outgassing in the vacuum tank. It avoids heating the whole tank and nevertheless permits a gain of a factor of 20 with respect to the pressure without bakeout.

7. - Alignment

The alignment of the front surfaces of the septa is made with a radial precision of ± 0.15 mm for a set of 2 magnets with common support. To this the precision of the relative alignment of the different vacuum tanks of ± 0.15 mm has to be added. The total precision for an assembly of 4 double magnets MST or 5 double magnets MSE therefore amounts to ± 0.3 mm. These magnets are installed in the accelerator as shown in Fig. 8.

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*) ETERNIT

8. - Current conductors and water cooling

Quick connections for 24 kA which are remotely controlled have been developed to connect the installed magnets to their water cooled bus-bars. In total, there are 2 copper bus-bars per polarity for the MST and 4 for the MSE. The cross-section of each bus-bar is 1544 mm^2. These bus-bars are connected to water cooled flexible cables of 750 mm^2 cross-section made of twisted copper. Two cables per polarity are used for the MST and 8 for the MSE. These cables are connected to the power supplies in the auxiliary buildings. The septum magnets have their own demineralised water circuit with a pressure of 25 bars. A filter of 25 microns is placed at the water inlet of each double magnet.

9. - Conclusions

18 vacuum tanks, each equipped with 2 thin or thick septum magnets, are installed in the two extraction channels of the SPS. 9 of these are used in operation in the first extraction channel since July 1976, with extracted beam intensities up to $7 * 10^{12}$ protons per pulse. The other 9 will come into operation before the end of 1977, when the second extraction channel will be commissioned. So far no incident due to the system itself has occurred to any of the double magnets installed in the accelerator.

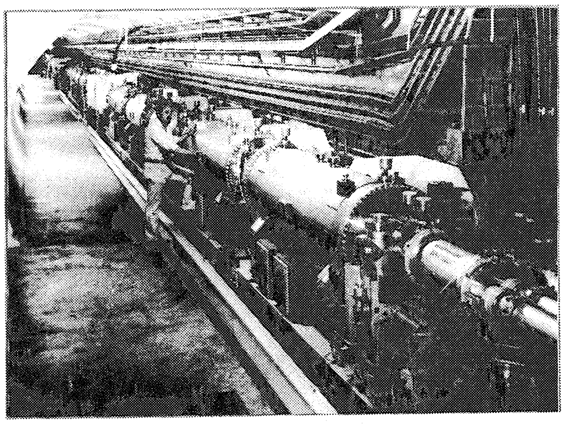

Fig. 8. Extraction channel in a long straight section of the SPS, 5 MSE tanks in the foreground and 4 MST tanks further upstream.

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