THE DEVELOPMENT OF LARGE APERTURE SEPTUM MAGNETS

FOR SLOW EJECTION

R.L. Keizer
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1. INTRODUCTION

The large aperture slow ejection system under construction for the CERN Proton Synchrotron requires in ss 16 a 2-turn septum magnet followed by two 3-turn magnets. The peak current density will be about 170 A mm\(^{-2}\). The water-cooled multicore conductors are 3 x 30 mm\(^2\) in cross-section.

This report describes the experience gained with a prototype 2-turn and a prototype 3-turn magnet.

The main features of these magnets may be summarized as follows:

1. The water-cooled conductors are formed by vacuum brazed copper tubes.

2. Copper tubes brazed to ceramic insulators replace the conventional metal O-seals on the inside water connections.

3. The core construction is based on the dry assembly of single laminations, clamped in a frame.

4. The magnet is designed to enable rapid replacement in radioactive surroundings.

5. Wherever possible aluminium oxide insulation is used in place of organic material.

2. MAIN PARAMETERS OF THE 2-TURN AND 3-TURN MAGNETS

Preliminary calculations by F. Schäff\(^1\) of the beam positions and beam profiles show that for fast ejection the required septum thickness should be \(\approx 6\) mm for the first (2-turn) magnet, and \(\approx 9\) mm for the subsequent (3-turn) magnets. These values have been confirmed by K.H. Kissler\(^2\) and K. Kubischta\(^3\).
The relevant parameters of the septum magnets are given in table 1.

Mechanically speaking, the 2-turn magnet is essentially the 3-turn magnet minus the innermost winding. This has two advantages:

1. Standardization of the magnet cores, only one type of magnet core being needed.

2. Standardization of septum coils. The same set of bending and soldering tools may be used for the production of a 3-turn, a 2-turn and possibly a 1-turn coil.
<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>2-turn magnet</th>
<th>3-turn magnet</th>
<th>2-turn magnet</th>
<th>3-turn magnet</th>
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<tr>
<td><strong>Physical parameters</strong></td>
<td></td>
<td>Required value</td>
<td>Actual value</td>
<td>Required value</td>
<td>Actual value</td>
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<tr>
<td>Proton energy</td>
<td>T</td>
<td>28 GeV⁴)</td>
<td>28 GeV⁴)</td>
<td></td>
<td></td>
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<tr>
<td>Deflection angle</td>
<td>θ</td>
<td>7.50 mrad</td>
<td>11.25 mrad</td>
<td></td>
<td></td>
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<tr>
<td>Dipole strength</td>
<td>B ds</td>
<td>0.71 Tm</td>
<td>0.71 Tm</td>
<td>1.08 Tm</td>
<td>1.08 Tm</td>
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<tr>
<td>Magnet current</td>
<td>I</td>
<td>12 kA⁴)</td>
<td>11.3 kA</td>
<td>12 kA</td>
<td>11.3 kA</td>
</tr>
<tr>
<td>Field strength</td>
<td>B</td>
<td>0.95 T</td>
<td>1.42 T</td>
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<td>Magnetic length</td>
<td>I_m</td>
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<td>0.760 m</td>
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<td><strong>Electrical parameters</strong></td>
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<td>1.125 mΩ</td>
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<td>Hot resistance coil</td>
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<td>0.810 mΩ</td>
<td>1.220 mΩ</td>
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<td></td>
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<td>Flat top voltage drop</td>
<td>U</td>
<td>9.2 V</td>
<td>13.7 V</td>
<td>21.1 V</td>
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<tr>
<td>30 ms rise time voltage</td>
<td>U</td>
<td>12.8 V</td>
<td>13.7 V</td>
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<td></td>
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<td>Energy consumption</td>
<td>Q_T</td>
<td>104 kW</td>
<td>155 kW</td>
<td></td>
<td></td>
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<tr>
<td>with 100% duty cycle</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Self inductance [0 Hz]</td>
<td>l_m</td>
<td>9.4 μH</td>
<td>19.6 μH</td>
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<tr>
<td>e.m. time constant</td>
<td>r_e.m.</td>
<td>12 ms</td>
<td>16 ms</td>
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<td><strong>Mechanical dimensions</strong></td>
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<tr>
<td>Iron length</td>
<td>I_{Fe}</td>
<td>0.720 m</td>
<td>0.720 m</td>
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<td></td>
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<tr>
<td>Gap height</td>
<td>h_g</td>
<td>30 mm⁴)</td>
<td>30 mm⁴)</td>
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<tr>
<td>Free gap width</td>
<td>w_g</td>
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<td>50 mm</td>
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<tr>
<td>Total gap width</td>
<td>w_t</td>
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<td>84 mm</td>
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<tr>
<td>Septum thickness</td>
<td>t</td>
<td>6 mm⁴)</td>
<td>6.3 mm</td>
<td>9</td>
<td>9.6 mm</td>
</tr>
<tr>
<td>Septum turns</td>
<td>n</td>
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<td>3</td>
<td></td>
<td></td>
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<tr>
<td>Total weight</td>
<td>w</td>
<td>220 kg</td>
<td>220 kg</td>
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<td><strong>Cooling parameters</strong></td>
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<tr>
<td>Min. pressure loss</td>
<td>ΔP</td>
<td>19 atm</td>
<td>19 atm</td>
<td></td>
<td></td>
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<tr>
<td>Min. water consumption</td>
<td>Q_w</td>
<td>35 l min⁻¹</td>
<td>49 l min⁻¹</td>
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<td></td>
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<td><strong>Miscellaneous</strong></td>
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<td></td>
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<tr>
<td>Expected lifetime</td>
<td>r_{mech}</td>
<td>± 2 °/oo</td>
<td>± 2 °/oo</td>
<td>± 2 °/oo</td>
<td>± 2 °/oo</td>
</tr>
<tr>
<td>Homogeneity main field</td>
<td></td>
<td>± 1.5 °/oo</td>
<td>± 2.5 °/oo</td>
<td>± 1.5 °/oo</td>
<td>± 2.5 °/oo</td>
</tr>
<tr>
<td>Integrated fringe field</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

**Table 1 - Main Parameters of the Prototype Magnets**
3. DESIGN PHILOSOPHY

3.1 Lifetime considerations

Pulsed septum magnets have a finite lifetime which may be expressed in Megapulses (Mp). If one analyses the various causes of magnet failure, the following partial lifetimes may be recognized:

1. The mechanical lifetime $\tau_{\text{mech}}$ is mainly determined by the soundness of the design, the quality of the soldered joints and seals. For instance, since the O-seals proved to be very troublesome, they have been replaced in the existing magnets by ceramic feedthroughs with vacuum brazed or hand brazed joints.

   The mechanical lifetime is determined to a high degree by wear-dependent factors like metal fatigue, joints which become porous because of electrolytic corrosion and insulation failure caused by mechanical wear.

2. The operational lifetime $\tau_{\text{op}}$ is influenced strongly by improper operation of the magnets. For example the absence of interlocks, bridged interlocks or wrongly connected cables will finally all cause a break-down of the system. Even with correctly installed interlocks the magnet may burn out because of interlock failure. Therefore the magnets have been equipped with a system of interlocks which is redundant in a few respects.

3. Finally, a radiation lifetime $\tau_{\text{rad}}$ may be distinguished. The lifetime is mainly determined by the total amount of radiation received by the septum insulation. Therefore the radiation lifetime may be expressed in Mp if the average dose is known. An attempt has been made to provide ceramic insulation on those points where the radiation will be the strongest.

Since radiolysis of the cooling water provokes copper transport inside the cooling ducts (removal from the hot spots and deposition
on cold places), it is necessary to check the flow regularly.

In general, experience\(^5\) with the existing septum magnets has shown that:

\[ 2 \text{Mp} \leq \tau_{\text{mech}}, \tau_{\text{op}} \leq 15 \text{Mp} < \tau_{\text{rad}} \quad [\text{existing magnets}] \]

This implied that under the actual conditions the mechanical construction and magnet protection has to be improved before radiation problems are tackled.

Since the prototype magnet has been pulsed $5 \cdot 10^6$ times (with Kapton insulation) without mechanical difficulties, one may write

\[ 5 \text{Mp} \leq \tau_{\text{mech}} \quad [\text{prototype}] \]

However, examination of components at this point indicated a lower limit of

\[ 10 \text{Mp} \leq \tau_{\text{mech}} \quad [\text{prototype}] \]

3.2 Symmetry conditions

The core is designed in such a way that any septum up to 9.6 mm thickness may be accommodated. The terminal blocks (see fig. 2) may be mounted either on the up-stream or on the down-stream side of the magnet whichever is the most convenient.

3.3 Radiation

The coil is designed as one unit and the magnet could possibly be dismantled with a manipulator or a long screwdriver. The current and water connections have been conceived with the same idea; they may also be unscrewed with a manipulator on extended tube spanner.
3.4 Maintenance

A great deal of attention has been given to the exchangeability of the various parts, so that any coil may be mounted in any core without any special adaptation.

3.5 Vacuum

The outgassing properties of the core are such that under normal conditions, i.e. with a properly outgassed core which has been exposed for several hours to ambient air, a vacuum of $10^{-6}$ Torr may be obtained in 5 hours and that the final pressure will be better than $2 \times 10^{-7}$ Torr. These conditions have been laid down by the vacuum section of the MPS Division 6).

4. MECHANICAL CONSTRUCTION PROTOTYPE MAGNETS

4.1 Core

The construction is shown in fig. 1. The 2-turn and 3-turn cores are identical. The following points are of interest:

**Laminations**

The laminations are made of HYPERM-4 strip 7) 0.5 mm thick. In order to have parallel polefaces it is necessary to stamp the laminations with the air gap slightly closing. After annealing, in a vacuum furnace the gap will on the average be parallel. Finally $\approx 20\%$ of the laminations is zinc phosphatized (4-5 $\mu$) polished and out-baked ($200\,^\circ C$) in a vacuum furnace. The quality of the insulation was checked by applying an a.c. voltage between two electrodes (see fig. 12 of ref. 8) and measuring the break-down voltage.

**Core assembly**

The laminations are aligned by means of a profiled stainless steel girder. The upper and lower notches define the position of the z-coordinate and the rear notches define the x-ordinate, both within $\pm 0.02$ mm. Four tie-bolts and two
box-shaped end-plates clamp the stack in longitudinal direction; average stack tension 10 kg cm\(^{-2}\). Filling factors exceeding 96 \(^{\circ}\) have been obtained.

Since the phosphate is rather hygroscopic, it was necessary to try out various combinations of phosphated and blank laminations. A sequence of 1 phosphated followed by 6 blank laminations turned out to yield low outgassing properties combined with not too severe eddy-current heating. [Pulse rise-time 30 ms and repetition rate 1 per s].

At regular intervals special laminations with increased gap height are mounted. In the recesses thus formed coil clamps are mounted.

Slots on the front face serve to hold in place the septum support rails.

After assembly of the core the surface in contact with the coil insulation and the recesses for the upper and lower retained are smoothed to diminish insulation wear.

Finally the cores are numbered for identification purposes.

**Rigidity of the core**

The rigidity of the core was investigated by measuring the flatness of the rear surface of the girder. The deformation remained within 0.1 mm for the temperature range investigated [20 °C to 60 °C].

4.2 **Coil construction**

4.2.1 **Manufacture**

Several prototypes have been constructed. All the designs were based on the formation of a multicore conductor by vacuum-brazing a number of OFHC copper tubes of square
cross-section. A determination of the optimum cooling duct size has been described in ref. 10. The final design is shown in fig. 2.

The manufacture proceeds in the following way:

1. **Resistance test**

   The resistivity of the tubes should be less than 1.76 \( \times 10^{-8} \) \( \Omega \) m.

2. **Bending**

   With a special bending jig the hard drawn tubes are given the correct shape. The places which will form the radii are h.f. annealed in an Argon atmosphere.

3. **Brazing**

   A number of tubes, to the equivalent of one turn, is then mounted in a brazing jig. For example, ten tubes 3 x 3 mm\(^2\) O.D by 1.5 x 1.5 mm\(^2\) I.D. will form the septum. Between the tubes strips of solder are placed on the places to be joined. In order to increase the flexibility the coil terminations are painted with an anti-wetting agent. Finally the coil is brazed in a vacuum furnace [810 \( ^\circ \)C].

4. **Trimming**

   The height of the conductors is then adjusted by pressing the copper conductors to the approximate height (correction 0.5 mm) and milling to size afterwards (correction \( \approx 0.2 \) mm). In this way a homogeneous wall thickness of the conductors is assured.

5. **Assembly of the individual turns**

   Hereafter follows the assembly of the inner conductor, the septum, the terminal blocks, ceramic feedthroughs and ceramic (Alsimag) substrates by hand-brazing [Castolin 1802 at 600 \( ^\circ \)C]. With smoke and x-ray tests eventual blockages are detected and removed. After chemical cleaning, pressure tests at 40 atm and
water flow tests, the turns are checked for vacuum leaks. Then follows the silver plating [10 μ ] which serves as a cleaning operation and makes easier the cleaning for vacuum operation. Finally the surfaces in contact with the Kapton insulation are polished with grade 700 abrasive paper.

6. Assembly of the coils

Two possibilities remain. If a Kapton insulation is desired the two or three individual coils are hand-brazed together, with equivalent metal strips inserted between the turns to serve as spacer. The contact surfaces of the terminal blocks are then machined and silver-plated. The recesses for the metal seals are left uncovered since otherwise the indium on the metal rings will dissolve the silver and form a brittle layer. The coil is then tested for water flow, electrical resistance and vacuum leaks. During the actual test in the magnet core the temperature rise in each individual tube, at the coil termination, is measured under dc operation.

If a ceramic insulation is required, the septa are sand-blasted and covered with plasma sprayed Al₂O₃. Then follows the normal assembly procedure. The inner conductors are always insulated with Kapton.

Finally the coils are numbered for identification purposes and the silver layer which will be in contact with the support rail (see fig. 3) is removed by polishing.

4.2.2 Holding of the coil

Several kinds of coil holders have been designed and tried, which all differ in the way the inner conductors are clamped (see figs. 3, 4 and 5).

Septum

The vertical movement of the septum is limited by two
septum retainers, made of 0.3 mm thick Armco material to which non-magnetic stainless steel edges are electron beam welded.

The horizontal movement inwards is limited by the above-mentioned stainless steel edges on the septum retainers while the displacement outwards is prevented by two support rails, made of soft iron (Armco), which lock into the core. The very high local pressure, exceeding 50 kg cm$^{-2}$, is supported by the aluminium substrates which are brazed to the rails. Because small pieces are taken, 25 x 3.5 x 0.8 mm$^3$, the flexibility of the rail is not impaired and even after 6 M-pulses the rails look like new. The 0.5 mm gap between two adjacent substrates is filled with Araldite (loaded with Al$_2$O$_3$ powder).

Fig. 5 shows the septum construction of the 2-turn coil. The septum retainer accommodates two turns only. However, the magnetic part of the retained fills completely the recess which is located to the left of the septum so that no field inhomogeneity results.

Inner conductors

The first construction which was tested made use of clips (fig. 3A), which clamp together the three inner conductors. The clips were made of Be-Copper tipped with pieces of alumina$^{11}$). This system has made 5 Mp without failure, but is somewhat risky and difficult to mount. In case of insulation failure, the inner conductors will be bridged.

The second construction using long springs (fig. 3B), turned out to have the wrong characteristics. After 0.9 M-pulses 80% of the springs had failed under fatigue and 40% of the Alumina substrates were fractured by impact loading.

A third construction using reinforced long springs (in order to increase the contact surface between spring and ceramic)
was used as a temporary measure since the recesses in the cores were not wide enough.

Finally the construction shown in fig. 4 was adopted. Flat springs are mounted on the support rails of the magnet and thick Be-Copper rods transmit the spring tension to the inner conductors. This system has been subjected to 0.5 M-pulses without failure.

4.2.3 Coils insulation

The quality of the insulation in pulsed magnets is proportional to the smoothness of the coil, core and insulation.

The Kapton\textsuperscript{12} insulation is shown in figs. 3, 4 and 5. The foil is 0.125 mm thick and that part of the insulation which is subjected to the horizontally directed magnetic pressure is always double or triple in thickness. The test voltage is 1000 V DC, insulation resistance better than 100 MΩ.

The inner conductors are mounted in a U-shaped channel made with a special bending jig which is heated to 250 °C for 24 hours. Between the conductors are inserted carefully cut Kapton strips. The edges of the centre conductor have been chamfered to eliminate the possibility of arcing or short-circuit.

The septum conductors are treated in a similar way. The upper and lower mass insulation is stuck to the septum retainer with Eastman cement. It was necessary to develop a special bending and mounting block to obtain a smooth surface. Attempts to cover the septum retainer with Al\textsubscript{2}O\textsubscript{3} or enamel insulation proved to be unsuccessful.

The inter-septum insulation can be either Kapton (fig. 3A) or plasma sprayed Al\textsubscript{2}O\textsubscript{3} (fig. 3B). The first insulation has been tested with 5M-pulses and the second with 0.9 Mp with practically no signs of wear.
Since originally the Kapton insulation was quite thin (see insert, fig. 3A) many difficulties were experienced with small metal flakes attracted to this region by the divergent magnetic field. A better solution using an overlapping insulation (see insert, fig. 3B) was finally developed.

The mass insulation on the support rails is formed by pieces of Alumina measuring 25 x 3.5 x 0.8 mm$^3$ which are hard-soldered. The abrasive wear is extremely small [in vacuum only].

5. **COOLING PARAMETERS**

5.1 The water flow

The choice of the optimum duct size has been reported in ref. 10. A comparison of the calculated water flow$^{13}$ and measurement is shown in fig. 6. Coils B4 and B6 are 3-turn prototypes with respectively 4 mm and 6 mm diameter feedthroughs (see fig. 2). The calculation takes into account the losses in the feedthroughs, but the influence of the terminal blocks has been neglected.

For the 2-turn coil similar results are shown. For all practical purposes the flow per turn is identical for the two coils. For operation in the extractor tank a minimum pressure drop of 19 atm is required.

5.2 DC temperatures

The measured electrical resistance $R_o$ of one turn is 0.375 m $\Omega$.

Assume that$^{13}$

$$R_T = R_o \left(1 + 0.004 \frac{T_w}{2}\right) \quad \Omega \quad , \quad (1)$$

and

$$\Delta T_w = 6 \times 10^{-2} \frac{0.24 I^2 R_T}{Q_w} \quad ^\circ C \quad , \quad (2)$$
Then the maximum dc current $I$ for a given water consumption $Q_w$ (l/min) and a fixed water temperature rise $\Delta T_w$ may be calculated. The results are shown in table 2.

<table>
<thead>
<tr>
<th>Pressure loss $P$ atm</th>
<th>Water flow $Q_w$ l/min$^{-1}$</th>
<th>Temperature rise $\Delta T_w$ °C</th>
<th>Hot resistance $R_T$ mΩ</th>
<th>dc current $I$ kA</th>
</tr>
</thead>
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<tr>
<td>14</td>
<td>14.5</td>
<td>40</td>
<td>0.405</td>
<td>10.0</td>
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<td>18</td>
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<td>17.6</td>
<td>60</td>
<td>0.421</td>
<td>13.2</td>
</tr>
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</table>

Table 2 - Dc performance of the 2-turn and 3-turn magnets

DC operation up to 10 kA is possible for long periods and 13 kA for shorter times. However, heat generation in the tank current connections has been neglected. For the extractor tank this amounts to about 8% of the total heat dissipated.
5.3 Pulsed performance

5.3.1 Temperatures

In order to limit wear of the Kapton insulation and to reduce fatigue effects the thermal expansion should be kept small and the magnets should be operated with maximum water flow. Lowering the inlet water temperature in order to permit a lower pressure drop will therefore have an adverse effect on the mechanical lifetime, since a lower pressure drop means less water flow.

Extensive calculations\(^{14}\) of temperatures in pulsed septa backed by many measurements have shown that it is possible to calculate the temperatures of new and clean septa only (\(\pm 10\%\)). During the operation thin insulating layers are formed inside the cooling ducts which render all calculations futile.

A calculation, pulse length \(t_p = 0.4\) s and cycle time \(t_r = 1.2\) s is shown in fig. 7A. The copper temperature \(T_{cu}(t)\) at the hot end of the septum charges varies rapidly, so does the water temperature \(T_w(t)\) which, however, does not show a discontinuity.

The expected temperature as a function of position along the coil at intervals of 0.1 s is shown in fig. 7B. These functions are estimated by calculating the septum and inner conductor temperatures separately and adding these two, taking into account the time delay caused by the difference in water velocity and distance travelled.

It was found in general that thermal equilibrium in the septum, i.e. when the maximum temperature does not increase any more, is reached after only a few pulses. The calculations also revealed that it is advantageous to have the cold water inlet on the terminal block connected to the septum (fig. 2). In this case the average \(T_{cu}(t)\) of respectively the septum and the inner conductor are less different, resulting in a more homogeneous expansion of the coil.
Measurements of the actual expansion of the coil show that in reality, due to friction between core and coil, the measured value is 50\% below the calculated one.

Septum temperatures measured as a function of time and pulse length, are shown in fig. 8. In both prototype magnets the dc equilibrium temperatures are reached after 0.8 s.

What could happen after the coil has been given 5 Mp is shown in fig. 9A. The expected and observed copper temperatures are as shown in table 3.

<table>
<thead>
<tr>
<th>Septum (fig. 2)</th>
<th>Calc. $T_{cu}^{\text{max}}$ at hot end $^\circ$C</th>
<th>Meas. $T_{cu}^{\text{max}}$ at hot end $^\circ$C</th>
<th>Time constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54</td>
<td>71</td>
<td>long</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>59</td>
<td>long</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>44</td>
<td>normal</td>
</tr>
</tbody>
</table>

Table 3

A comparison of measured and calculated septum temperatures after 5 M-pulses

The measured water temperatures, however, are in good agreement with the calculated values. Since the copper temperatures were all equal at the start of the tests the conclusion may be drawn that gradually a thermally insulating layer had been formed on the inside of the tube. The cooling water was demineralized and no oxydation reducing additives have been used.
5.3.2 Maximum ratings

The performance of the prototype magnets may be read from fig. 9B, which is an extension of table 2 into the pulsed region.

With formula (2), chapter 5.2, the expected dc temperatures for pulse currents between 8 kA and 16 kA have been calculated. If the experimentally designed shape of the function $T_{cu}(t)$, fig. 8A, for 11.8 kA, is assumed to be valid for any current $I(t)$, the pulse length which will cause a given water temperature rise may then be evaluated.

The expected PS cycle times are very long compared with the thermal time constant of the magnets ($\approx 300$ ms). This is especially the case in the high energy region. Therefore it is possible to give the maximum ratings independent of the duty factor since thermal equilibrium in the magnets is reached after one or two pulses.

5.4 Thermal time constant and burn-out time

The thermal parameters of the coil are given in table 4. The calculations are based on ref. 13. The measured values are taken from fig. 8. However, formula 12 of ref. 13, which has been determined empirically to give the correct asymptotic temperature and the correct initial temperature rise, does not yield a reliable time constant.

With no water flow the time necessary for a $70 \degree C$ temperature rise of the septum is $600$ ms. This is slow enough for the electronic protection to react. However, thermo-couples mounted on the current and water conductors to the magnets should be far away from thick copper blocks. For the inner conductor, for example, the burn-out time is already 4 times that of the septum. This signifies that the septum will reach a temperature of $300 \degree C$ by the time the inner conductor has risen to $90 \degree C$. 
<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Septum</th>
<th></th>
<th>Inner Conductor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
<td>Measured</td>
<td>Calculated</td>
<td>Measured</td>
</tr>
<tr>
<td>Cross-section copper</td>
<td>$A_{Cu}$ (cm$^2$)</td>
<td>0.675</td>
<td>1.332</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-section water</td>
<td>$A_{w}$ (cm$^2$)</td>
<td>0.225</td>
<td>0.450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetted perimeter</td>
<td>$A_c$ (cm)</td>
<td>6.0</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water flow per turn</td>
<td>$Q_w$ (l min$^{-1}$)</td>
<td>15</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water velocity</td>
<td>$v$ (ms$^{-1}$)</td>
<td>11.1</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet current</td>
<td>$I$ (kA)</td>
<td>11.8</td>
<td>11.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electr. resistance</td>
<td>$R_o$ (m$m$)</td>
<td>0.275</td>
<td>0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat dissipation</td>
<td>$Q_o$ (cal s$^{-1}$)</td>
<td>9150</td>
<td>3390</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>$M$ ($^\circ$C s$^{-1}$)</td>
<td>162</td>
<td>41.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>$N$ (s$^{-1}$)</td>
<td>119</td>
<td>3.9</td>
<td>$\lambda = 1.3$</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>$P$ (s$^{-1}$)</td>
<td>29.3</td>
<td>9.6</td>
<td>$\lambda = 0.72$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at $X = 95$ cm,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_{septum} = 103$ cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_{inner} = 75$ cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water temperature rise</td>
<td>$T_w - T_0$ ($^\circ$C)</td>
<td>37.5</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Copper temperature rise</td>
<td>$T_{Cu} - T_0$ ($^\circ$C)</td>
<td>50.3</td>
<td>46</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Thermal time constant</td>
<td>$\tau_{th}$ (ms)</td>
<td>400</td>
<td>280</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Burn-out time for 70 $^\circ$C temp. rise</td>
<td>$t_{20-70}$ (ms)</td>
<td>600</td>
<td>--</td>
<td>2300</td>
<td>--</td>
</tr>
<tr>
<td>Temp. gradient</td>
<td>$\frac{dT_{Cu}}{dt}$ ($^\circ$C s$^{-1}$)</td>
<td>115</td>
<td>114</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4

The thermal parameters of the magnet coils
6. THE VACUUM

6.1 Experience with dry-stacked cores

The choice of a dry-stacked core construction was based on favourable results obtained in other laboratories\textsuperscript{16, 17}, outgassing tests made at CERN and the requirements that no organic material should be used in the magnet construction. In table 5 dry-stacked cores with an unknown inorganic insulation are compared with epoxy bound cores. The final pressures obtainable with dry-stacked cores are orders of magnitude lower, but the high absorption of these cores caused by hygroscopicity of the phosphate or oxides, requires special techniques and extra preparation time. Therefore these cores could be applied only in vacuum sections which are not very frequently opened.

6.2 Test installation

The 170 \( \ell \) vacuum tank is provided with a 70 \( \ell/s \) Balzer turbo-molecular pump (TVP 250) and a 70 \( \ell/s \) ion pump. With a Viton seal the final pressure is about \( 5 \times 10^{-7} \) \( \text{T} \). A vacuum better than \( 10^{-8} \) \( \text{T} \) has been obtained with an aluminium wire seal.

The current feedthrough is similar to the one developed for the extractor tank, thus the feedthrough has been tested simultaneously.

Furthermore, special feedthroughs are mounted for the wires and thermo-couples (Thermocoax) for the CAMAC protection system. Spare thermo-couples are provided to measure the core temperature.
<table>
<thead>
<tr>
<th>Construction</th>
<th>Outgassing rate in Tl s(^{-1}) cm(^{-2})</th>
<th>Pressure T</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry stacking, baking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>after 5 hours</td>
<td>1.5 (10^{-6})</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>after 24 hours</td>
<td>2.3 (10^{-7})</td>
<td>1.2 (10^{-7})*</td>
<td>Iron oxide insulation formed by exposure to air at 600 °C</td>
</tr>
<tr>
<td>after 100 hours</td>
<td>4.0 (10^{-8})</td>
<td>7.0 (10^{-8})</td>
<td></td>
</tr>
<tr>
<td>Dry stacking, with baking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>after 5 hours</td>
<td>5.0 (10^{-7})</td>
<td>---</td>
<td>93 °C in dry Argon atm, exposed to air for 3 hours</td>
</tr>
<tr>
<td>after 24 hours</td>
<td>6.0 (10^{-8})</td>
<td>---</td>
<td>heated to 170 °C in air cooling down in vacuum</td>
</tr>
<tr>
<td>after 100 hours</td>
<td>7.0 (10^{-9})</td>
<td>4.8 (10^{-10})</td>
<td></td>
</tr>
<tr>
<td>Epoxy bonded core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>after 5 hours</td>
<td>3.5 (10^{-7})</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>after 24 hours</td>
<td>7.0 (10^{-8})</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>after 100 hours</td>
<td>1.8 (10^{-8})</td>
<td>(\approx 10^{-7})</td>
<td></td>
</tr>
<tr>
<td>Base pressure</td>
<td></td>
<td>8.0 (10^{-7})</td>
<td>200 °C for 30 hours in vacuum. Lower base pressures are attainable.</td>
</tr>
<tr>
<td>old design epoxy ej. magnet</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Base pressure</td>
<td></td>
<td>2.0 (10^{-9})</td>
<td></td>
</tr>
<tr>
<td>new dry stacked ac ej. magnet</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Table 5

A comparison of dry stacked and epoxy bonded cores
6.3 Outgassing test results

6.3.1 Measuring procedures

Heavy outgassing of the originally proposed core has lead to a series of vacuum tests during which the composition of the core was modified several times. Since it is very useful to have the complete set of data available the test results will be presented in detail.

Firstly the vacuum requirements were specified in the following way:

1. The ion pumps must be switched on at $5 \times 10^{-5}$ Torr after maximum 3 hours of pumping.

2. A pressure of better than $3 \times 10^{-6}$ Torr should be obtained after 5 hours of pumping.

3. The vacuum should preferably be better than $3 \times 10^{-7}$ Torr after 24 hours, but a vacuum of $6 \times 10^{-7}$ Torr will still be accepted.

4. The base pressure after 4 days of pumping should be lower than $2 \times 10^{-7}$ Torr.

Secondly the vacuum tank was then provided with a roughening system and ion pump in such a way that the pumping capacity per magnet is roughly equal to that of the extractor tank. Unfortunately the vacuum gauges were wrongly positioned so that the pressures measured below $10^{-6}$ Torr are very pessimistic. The ion pump readings, on the other hand, gave rather optimistic values. The shown pressures are all "pessimistic" measurements.

A series of characteristic tests was then designed.

1. The initial out-baking test

The complete magnet or core is treated to $\approx 100^\circ C$ in air with specially constructed heater panels. The heating-up takes
about 8 hours (fig. 10) with 1 kW of heating power dissipated into a core weighing 200 kg. The tank is then closed and pumped. The magnet is still 90 °C after 24 hours and stays warm for 3 to 4 days. This test represents the first pump down after a long shut-down.

2. **The minor repair test**

   The tank is filled with dry nitrogen and kept closed. After 2 or 5 hours the pumping characteristics are measured. This procedure represents the opening of the vacuum section without touching the magnets or a minor repair to the mini-scanner with nitrogen overpressure.

3. **The major repair test**

   The tank is filled with dry nitrogen for 15 minutes and then opened completely. The magnets are exposed to ambient air for 2 or 5 hours. The pumping characteristics are then measured. This test represents the exchange of a faulty septum magnet. The spare magnet could have been stored in dry nitrogen for instance.

4. **The implosion test**

   The tank is filled with air for 1 hour. The tank remains closed during this interval. Pump-down characteristics are then measured. This procedure represents an implosion, for instance the bellows could fail somewhere in the vacuum section.

   The core contains about 1400 laminations, 0.5 mm thick, which provide an outgassing surface \( A_{\text{outgassing}} \) defined as

   \[
   A_{\text{outgassing}} = \text{circumference of one lamination, including the stamped holes} \\
   \times \text{core length} \\
   = 106 \times 71 \\
   = 7500 \text{ cm}^2 .
   \]
All the cores were compressed with a pressure of \( \approx 10 \text{ kg cm}^{-2} \). The tank capacity is 170 \( \ell \) and the core has a volume of about 30 \( \ell \), so that the effective volume is 140 \( \ell \). At \( 10^{-6} \) Torr the outgassing rate of the tank is \( \approx 2.8 \times 10^{-6} \text{Tls}^{-1} \). (with Viton seals).

6.3.2 The all-phosphated core

The phosphated core was assembled using the laminations in the state they were received from the surface treatment works. The geometric mean value of the roughness is then 0.5 \( \mu m \) causing an average slit width between two dimensions of 1 \( \mu m \) through which the absorption and outgassing takes place. The phosphate is very hygroscopic, the chemical formula being

\[
\text{Zn}_3(\text{PO}_4)_2 \cdot 4 \text{H}_2\text{O} + \alpha \text{Zn}_2\text{Fe}(\text{PO}_4)_2
\]

where \( \alpha \) is small and forms a deeper lying layer in direct contact with the metal surface. Consequently the first pump-down curve (fig. 11) is very unsatisfactory.

The bake-out run, curve 1, shows that the initial outgassing is very high, but lasts only a couple of hours. The lowest pressure attained, \( 6 \times 10^{-7} \) Torr, is determined rather by the Viton seal and the cleanness of the tank than by outgassing of the core. The "optimistic" ion pump reading was \( 3 \times 10^{-7} \) Torr in this case.

The subsequent cycles show acceptable curves for the "minor repair" test with dry nitrogen, curves 2 and 3. However, a moderate period of time, 1 hour, in contact with a limited volume of air, 140 litres, changes the curve drastically. The explanation is probably as follows:

140 \( \ell \) of saturated air, temperature 20 \( ^\circ \text{C} \) and atmospheric pressure contain 2.6 g of water. On the other hand the maximum amount of crystal water in a core containing 1400 laminations, each covered on both sides with 5 \( \mu m \) of phosphate, density 3.5,
is approximately 160 g. Therefore a partially dessicated core can easily absorb 2.6 g of water.

Other indications that this conjecture is correct are:

1. Curves 4 and 5 run more or less parallel. The assumption is made that the pumping capacity remains constant over the whole pressure range. The ratio of the pumping times at a given pressure should then be proportional to the ratio of the amounts of water absorbed. This ratio in the lower pressure range is roughly 5. Therefore the maximum amount of moisture taken up by the core is then 13 grams of water during an exposure to air of 2 hours.

2. The ratio of the pumping times at 8 \(10^{-5}\) Torr between curves 0 and 4, which also run parallel, is \(\approx 7\). Hence a fully saturated core should have lost after the bake-out run \(7 \times 13 = 91\) g of water.

At \(10^{-6}\) Torr the outgassing rate of the core, curve 1, was measured to be \(3.6 \times 10^{-6}\ \text{Torr s}^{-1}\) which yields a specific outgassing rate of \(4.8 \times 10^{-10}\ \text{Torr s}^{-1} \text{ cm}^{-2}\). This value is comparable with similar measurements done in Brookhaven \((7.0 \times 10^{-9}\ \text{Torr s}^{-1} \text{ cm}^{-2}\), heating to only 93 °C). See table 5.

6.3.3 The diluted cores

Since the "major repair" curves are unacceptable, an "untreated" core was made up of very clean untreated laminations which were clamped together with a pressure of about 10 kg/cm². The first pump-down (fig. 12, curve 4) was very promising. With respect to the all-phosphated core an improvement of orders of magnitude has been obtained.

Since eddy current effects could not be neglected entirely a second experimental core was constructed with one phosphated lamination to every five blanks. The phosphated laminations were carefully polished, cleaned, dried and underwent
a bake-out in a vacuum furnace. The ratio of the pumping times, with respect to an untreated core (fig. 12, curves 3 and 4), is 3 at $10^{-5}$ Torr and 2.3 at $10^{-6}$ Torr. However, compared with a 100% phosphated magnet (fig. 11, curve 1), a shortening of pumping time of 200 x was obtained. The difference being caused by:

1. a 7 x reduction of the amount of phosphate,
2. a smaller gap between the laminations, since there was either no phosphate or the phosphate surface was polished,
3. a much cleaner core initially.

During the bake-out run (fig. 13, curve 1) much lower pressures were obtained than with the phosphated core, the graph indicates 3.3 $10^{-7}$ Torr, but the ion pump reading was 1.0 $10^{-7}$ Torr.

However the "long repair test" turned out to be unsatisfactory. In this case the ion pump reading lies in the cross-hatched region.

Finally a complete magnet was constructed with a ratio of one phosphated lamination to every 6 blanks. All laminations were given a bake-out before assembly.

The initial pump-down (fig. 12, curve 2) shows that the Kapton and ceramic insulation caused considerable outgassing; with respect to the first curve (1) an improvement in pump-time of 10 x was obtained.

The bake-out run (fig. 14, curve 0) shows an improvement of only 3 x with respect to the all phosphated core (fig. 11, curve 0). This might be due to the much higher temperature of the diluted core at equivalent pressure.

The major repair test cannot be compared directly because of the difference in exposure time, 2 hours and 5 hours respectively. Taking this difference into account the ratio of the pump-times at
Therefore the improvement is more than expected from the reduction of phosphate alone (7 x).

The minor repair tests (figs. 11 and 14, curve 2) also show an improvement of 2 x. This could mean that the diluted core outgasses better or that the gain of 35 x in the previous case has directly to do with the humidity absorbed. The pulsed tests show a marginal increase of tank pressure, the core temperature was not seriously affected by eddy current heating [ΔT = + 20 °C after one day of pulsing].

6.4 Conclusion

The diluted core may still be improved by changing the Kapton insulation and using better quality ceramic for the insulation of the control leads and thermo-couples. For a major repair lasting several hours the magnets are acceptable. With margins like the difference between optimistic and pessimistic pressure readings and the bigger pumping capacity of the extractor tank and metal seals instead of Viton joints, these magnets should be able to have characteristics which lie in the shaded region for most of the cases where the vacuum has to be interrupted for a short period only.

7. MAGNETIC MEASUREMENTS

7.1 Magnetic properties of the core material

The laminations are stamped from Hyperm-4 strip 0.5 mm thick. In order to have the high permeability and low coercitive force \( H_c = 24 \, \text{A} \, \text{m}^{-1} \) (see fig. 15) as claimed by the manufacturer, it is necessary to anneal the material after stamping in a dry hydrogen atmosphere at 1250 °C for at least 6 hours. Since such
a furnace is not available at CERN the treatment was done in a vacuum furnace [with oil diffusion pump and baffle] [at 1100-1150 °C ] for 6 hours. Although the results are not as good as those obtained by the manufacturer the magnetic properties are far superior to those of Armco soft iron.

An alternative choice would have been, for instance, Vacoflux (50 °/o C o and 50 °/o P c ) which saturated at a much higher induction, thus rendering the core more versatile. Apart from difficulties in obtaining the required width, the presence of Co excludes the application in a nuclear radiation field.

7.2 Field calculations

7.2.1 Main field and fringe field

The influence of the septum geometry, like thickness of the insulation, size and magnetic properties of the support rails, size of the cooling ducts, has been investigated with the 2-dimensional computer program MAGNET. It was found that magnetic support rails are preferable to non-magnetic ones, because of their lower stray field.

The clearance between conductor and core is very important for field distortions in the per mil range. This is especially the case with the horizontal clearance shown in fig. 16, which strongly influences the internal field. The influence of the water ducts, short range, is clearly visible. The calculated homogeneity of the main field remains within 1 °/oo over a large part of the cross-sectional area [80 °/o for the 3-turn magnet and 65 °/o for the 2-turn magnet]. The most serious deviations are in the corners and near the septum. These areas are less important statistically.

The calculation shows that the fringe fields will be very similar in the two cases.
7.2.2 The end field

The end field of the 3-turn magnets is shown in fig. 17. The position of the return coil c was chosen such that the total flux in the iron yoke in the median plane was identical to the flux in fig. 16. The equivalent magnetic length of the end field turned out to be 0.47 x gap height.

7.3 Field measurements

The pulsed field measurements were done with a coil and integrating DVM controlled by variable START, STOP and RESET pulses which were received from a cascade counter triggered by the magnet power supply. Since the test power supply has a very strong current ripple [4.5 %] and is not very stable, a compensating coil and RC filter were necessary to obtain stable readings in the possible range. Since the cross-section of the coil, 14 x 14 mm$^2$, is rather large with respect to the dimensions of the magnet gap, 30 x 50 mm$^2$, only a few points could be measured.

With a long coil [1.35 m] the homogeneity of the integrated main field of the 3-turn prototype magnet was measured. The start pulse was delayed about 150 ms. The pulse rise time was of the order of 30 ms.

Fig. 18 shows that a reasonable agreement with the calculation was obtained.

The integrated fringe field however, turned out to be quite different from the calculation. The influence of the current conductors which are near the magnet was not investigated. The thick end plates [6 mm] did not cause any serious problems.

8. MAGNET PROTECTION

A standardized modular septum magnet protection system has been designed and tested which is used for all pulsed and dc septum magnets under construction.
A block diagram (fig. 19) shows which information is received regarding the state of the magnet in the vacuum tank.

The MAGNET SURVEY BOX receives the data and produces a MAGNET FAULT signal which goes to the control panel of the magnet power supply.

In case of bad vacuum the power supply will be switched off and the cooling water will be cut \[e.m. \text{ valve}\].

A connection is provided for computer acquisition of data \[\text{STAR STATUS}\].

An EARTH FAULT circuit surveys the insulation between the coil and the magnet core and tells when the magnets touches the tank wall. A FAST PROTECTION module detects overheating of the coils or a short-circuit between the windings \[\text{principle: wheatstone bridge with a polarized relay}\].

A thermo-couple measures the cooling water temperature. Furthermore two Eletta's monitor the water flow in the tank and water-cooled cable. The water pressure is checked on the inlet and outlet, thus providing a second flow measurement.

An EMERGENCY switch is mounted on the tank.

A PULSE COUNTER indicates the number of pulses received by the magnet.

9. **LIFE TESTING**

9.1 **Test procedure**

Since the duty factor of the test power supply is rather low, about 20% at 12 kA, life testing with 700 ms pulses would yield only 0.7 M-pulses per month. In order to speed up testing the magnets are subjected to "equivalent" pulses which have the same flat top current, but are shorter in length. The water pressure however, has been reduced so that the thermal expansion, as measured with dial gauges, remains unchanged.
The following table compares the "normal" operating conditions with the "equivalent" conditions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>&quot;Normal&quot; Conditions</th>
<th>&quot;Equivalent&quot; Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>11.3 kA</td>
<td>12 kA</td>
</tr>
<tr>
<td>Pulse length</td>
<td>700 ms</td>
<td>200 ms</td>
</tr>
<tr>
<td>Cycle time</td>
<td>≈ 2000 ms</td>
<td>≈ 1000 ms</td>
</tr>
<tr>
<td>Water pressure drop</td>
<td>19 kg/cm²</td>
<td>5 kg/cm²</td>
</tr>
<tr>
<td>Water flow</td>
<td>45 l/min</td>
<td>21 l/min</td>
</tr>
<tr>
<td>Measured expans. of septum</td>
<td>0.26 mm</td>
<td>0.26 mm</td>
</tr>
<tr>
<td>Calculated expansion</td>
<td>0.45 mm</td>
<td>0.45 mm</td>
</tr>
</tbody>
</table>

Table 6

A comparison of operating and test conditions

The magnets have been tested in a tank specially designed to accommodate a great variety of septum magnets and their corresponding water and current feedthroughs.

9.2 Test results

The test programme which has been carried out hitherto may be summarized as follows:

1. 4.8 M-pulses with the prototype 3-turn coil in the test tank, Kapton insulation [table 7].
2. 0.9 M-pulses with the same coil in the test tank, Al$_2$O$_3$ septum insulation [table 8].

3. 1.1 M-pulses with 6 different production magnets, Kapton insulation, in the test tank [tables 9 and 10]

Furthermore, experience has been gained with a set of three magnets in the extractor tank pulsed with the test power supply 0.4 M-pulses] and with approximately 1.0 M-pulses with the same tank installed in the ring.

<table>
<thead>
<tr>
<th>Test with prototype core, 3-turn coil [4 B], 8.2.71</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of days</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>18</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>38</td>
</tr>
<tr>
<td>44</td>
</tr>
<tr>
<td>52</td>
</tr>
<tr>
<td>62</td>
</tr>
<tr>
<td>82</td>
</tr>
<tr>
<td>90</td>
</tr>
</tbody>
</table>

Table 7
Test results with the prototype 3-turn coil and Kapton insulation
The construction of the coil is shown in figs. 2 and 3A. The Armco support rails turned out to be the weakest component initially. The experiment with Kapton insulation [table 7] was halted at 4.77 M-pulses. Inspection of the insulation indicated a lifetime greater than 10 M-pulses. No difficulties were experienced with the magnet protection system or ceramic 12 kA feedthroughs which were tested simultaneously. No particular attention was given to the outgassing properties of the core at this stage.

<table>
<thead>
<tr>
<th>Test with production core No. 1, 3-turn coil [3 B], 31.8.71</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of days</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>17</td>
</tr>
</tbody>
</table>

Table 8

Test results with the prototype 3-turn coil

where the septum insulation is plasma sprayed $\text{Al}_2\text{O}_3$.
The next stage was to dismantle the 3-turn coil with 4 mm diameter insulators and to cover the septum conductor with plasma sprayed Al$_2$O$_3$ (fig. 3B). The spring construction was also changed. It was then discovered that a small fatigue crack had developed in one of the terminal blocks and had been opened by subsequent manipulation. As a result of this experience the terminal block construction was slightly modified. After 0.92 M-pulses (see table 8), it was found that most of the springs and ceramics were broken due to fatigue and the rigidity of the springs. The spring construction therefore was changed at a later stage and the elastic energy is now stored in flat springs mounted on the Armco support rails (fig. 4). The Al$_2$O$_3$ septum insulation did not show any sign of wear.

<table>
<thead>
<tr>
<th>No. of days</th>
<th>Pulse count M-pulses</th>
<th>Vacuum pressure Torr</th>
<th>Component failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Armco rails</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Brazed ceramic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Earth fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water leaks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fatigue cracks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fixat. screws</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reinf. long springs</td>
</tr>
</tbody>
</table>

**Table 9 - Test results with the production magnets**
The first test results for the first three production magnets are shown in table 9. The 4 mm bore ceramic water feedthrough (fig. 2) was replaced by a 6 mm type. Initially this caused some delay because of water leaks due to joints difficult to braze. Also the soft electro-deposited silver coating on the septa caused frequent short-circuits between the septum and the Armco rails [Earth fault, table 9]. The large springs (fig. 3B) were reinforced, but the 1 mm Alumina supports were still fractured.

Since test in the extractor tank revealed a high initial outgassing rate the core construction was modified. The ratio of phosphated to blank laminations was taken to be 1:6 [See chapter 6] which reduced drastically the outgassing rate. The long springs were replaced by flat springs (fig. 4). The results are shown in table 10. Only in one case a small water leak was discovered which was very probably not the magnet, but a leaky joint in the feedthrough. The septum was polished over its entire length and all the silver was removed from the region in contact with the Armco support rails. The ceramic was ground as shown in fig. 4, detail A, to increase the insulation overlap.
<table>
<thead>
<tr>
<th>Number of days</th>
<th>Pulse count (M-pulses)</th>
<th>Vacuum pressure (Torr)</th>
<th>Component failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not pulsed</td>
<td>Pulsed</td>
<td>Armco rails</td>
</tr>
<tr>
<td>Test with core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 35, 3-turn coil No. 5, Kapton insulat.</td>
<td>23.12.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>0.07</td>
<td>6.0 \times 10^{-6}</td>
<td>1.8 \times 10^{-6}</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>2.4 \times 10^{-6}</td>
<td>1.6 \times 10^{-6}</td>
</tr>
<tr>
<td>11</td>
<td>0.25</td>
<td>1.1 \times 10^{-6}</td>
<td>1.6 \times 10^{-6}</td>
</tr>
<tr>
<td>12</td>
<td>0.32</td>
<td>1.6 \times 10^{-6}</td>
<td>1.6 \times 10^{-6}</td>
</tr>
<tr>
<td>Test with core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 36, 3-turn coil No. 6, Kapton insulat.</td>
<td>13.3.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>0.08</td>
<td>6.7 \times 10^{-6}</td>
<td>7.3 \times 10^{-6}</td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td>1.7 \times 10^{-6}</td>
<td>1.2 \times 10^{-6}</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>1.7 \times 10^{-6}</td>
<td>1.7 \times 10^{-6}</td>
</tr>
<tr>
<td>Test with core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 31, 2-turn coil No. 2, Kapton insulat.</td>
<td>16.3.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>0.08</td>
<td>3.0 \times 10^{-6}</td>
<td>2.2 \times 10^{-6}</td>
</tr>
<tr>
<td>Test with core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 35, 3-turn coil No. 5, Kapton insulat.</td>
<td>21.3.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>0.01</td>
<td>6.1 \times 10^{-7}</td>
<td>8.5 \times 10^{-7}</td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td>8.1 \times 10^{-7}</td>
<td>1.2 \times 10^{-6}</td>
</tr>
<tr>
<td>Test with core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 31, 2-turn coil No. 2, Kapton insulat.</td>
<td>24.3.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>0.01</td>
<td>5.5 \times 10^{-6}</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>6.5 \times 10^{-6}</td>
<td>---</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>4.6 \times 10^{-6}</td>
<td>1.1 \times 10^{-6}</td>
</tr>
</tbody>
</table>

Table 10 - Test with the low outgassing production magnets

*) Cores diluted 1:6, no bake-out
10. **EXPECTED RADIATION DAMAGE**

10.1 **Introduction**

"During the last years the intensity of the CPS has increased and a further substantial increase is expected as soon as the CPS Booster comes into operation\(^{23}\). The planned intensity is 5 Tppp up to 1975 and will exceed 10 Tppp thereafter\(^{24}\).

Calculations of the expected doses of activity induced during operation of the machine have been compared with experimental data by Hoyer, Goebel and Schindl\(^{25, 26}\). The estimation of the radiation lifetime of the various parts of the magnet coil is based mainly on these two reports.

The beam loss distribution around the extractor magnets may be calculated by assuming a linear source, 1 m long, placed at the centre of the septum of the first extractor element. The estimated radiation pattern for 20 Gev protons is shown in fig. 20. The inner conductors are irradiated mainly by FAST NEUTRON (FN), while the septa, apart from the energy loss sustained by the primary protons will receive a mixture of DN and high energy particles (HEP). The influence of the magnetic field on the radiation pattern may be neglected since the calculation serves only to determine the order of magnitude of radiation damage.

As shown, the radiation level in the inner conductors is substantially lower than in the septum. The FN distribution is derived from calculations for 20 GeV protons \([\text{fig. 8}^{25}]\) and 50 MeV protons \([\text{fig. 12}^{25}]\). In the two cases the FN distributions are very similar. The HEP calculation is based on fig. 8\(^{25}\) and the knowledge that the angular distribution is not energy-dependent \([\text{fig. 5}^{25}]\).

Furthermore, the assumptions have been made that the proton intensity at the loss point will not exceed 2\(^{\circ}\)/o of 10 Tp per pulse and that the minimum beam height will be 10 mm.
The radiation resistance of Kapton is given in table 11, for which a value of $2 \times 10^{10}$ rad in vacuum has been assumed.

<table>
<thead>
<tr>
<th>Kind of radiation</th>
<th>Dose</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation in air \textsuperscript{27) }</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>$4 \times 10^9$ rad</td>
<td>Still flexible</td>
</tr>
<tr>
<td>Electrons</td>
<td>$6 \times 10^9$ rad</td>
<td>$50%$ decrease in elongation</td>
</tr>
<tr>
<td>Neutrons and Gammas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tensile strength</td>
<td>$5 \times 10^9$ rad</td>
<td>darkened, tensile str. $50%$</td>
</tr>
<tr>
<td>- Elongation $65 , ^{\circ}$/o</td>
<td>$10^{10}$ rad</td>
<td>darkened tough, elong. $6%$</td>
</tr>
<tr>
<td>Irradiation in vacuum \textsuperscript{28) }</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tensile strength</td>
<td>$4 \times 10^{10}$ rad</td>
<td>tensile strength still $90%$</td>
</tr>
<tr>
<td>- Elongation $65 , ^{\circ}$/o</td>
<td>$4 \times 10^{10}$ rad</td>
<td>elongation $13%$</td>
</tr>
<tr>
<td>Outgassing</td>
<td>$10^9$ rad</td>
<td>less than outgassing rate of mylar</td>
</tr>
</tbody>
</table>

Table 11

Radiation properties of Kapton film

10.2 Radiation damage of the magnet coil

For protons exceeding 1 GeV in energy the specific energy loss in matter is constant. In copper the linear energy transfer coefficient $dE/dx$ is $1.44 \, \text{MeV} \, g^{-1} \, \text{cm}^2$. Since $1 \, \text{rad} = 6.24 \times 10^7 \, \text{MeV} \, g^{-1}$, the radiation dose per pulse $D$ received by the septum will be...
\[ D = \frac{0.02 \times 10^{12}}{6.24 \times 10^7} \times 1.44 \times 0.6 \]
\[ = 7.7 \times 10^3 \text{ rad p pulse of 10 Tp.} \]

The copper cross section irradiated will be 0.6 cm\(^2\) if the septum is 6 mm thick, and the beam is 10 mm high. The copper septum and Al\(_2\)O\(_3\) insulation can absorb doses exceeding 10\(^{12}\) rad. The expected radiation lifetime of an Al\(_2\)O\(_3\) insulated septum will therefore be:

\[ \tau_{\text{rad (septum)}} > 10^8 \text{ pulses of 10 Tp}. \]

For Kapton, with the chemical composition \[ C_{22}H_{10}N_{2}O_{4}n \]
one finds for 20 GeV proton energy

\[ \frac{dE}{dx} (p, \text{Kapton}) = 1.82 \text{ MeV g}^{-1} \text{ cm}^2. \]

The radiation dose per pulse therefore becomes

\[ D = \frac{1.82}{1.44} \times 7.7 \times 10^3 \]
\[ = 9.7 \times 10^3 \text{ rad p pulse of 10 Tp} \]

Hence

\[ \tau_{\text{rad (Kapton)}} > 2 \times 10^6 \text{ pulses of 10 Tp}. \]

The lifetime is rather short and the use of Kapton as septum insulation should therefore be avoided once the high intensity is reached.
The average FN flux in the inner conductor (fig. 20) will be $0.5 \times 10^{10}$ FN cm$^{-2}$ per incident Tp. Hence for 2% of $10^{13}$ protons the flux will be $10^9$ FN cm$^{-2}$. The radiation dose will be, if a conversion factor of $3 \times 10^{-8}$ rad per FN cm$^{-2}$ is used.

$$D\text{ (inner conductor)} \approx 30 \text{ rad per pulse of 10 Tp}.$$ For Kapton the radiation lifetime will be

$$\tau_{\text{rad (Kapton)}} > 7 \times 10^8 \text{ pulses of 10 Tp}.$$ Hence for the inner conductor Kapton may be used, since the mechanical lifetime is not expected to exceed the radiation lifetime in this case.

Acknowledgments:

The author would like to thank, without mentioning names - the list would be too long - all the persons involved in the development of these magnets. Without the availability of techniques like plasma spraying, vacuum brazing, electron beam welding to mention only a few, the development of reliable magnets with low outgassing properties would have been impossible.
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Effects of radiation on materials and components  
CERN 70-5

Distribution: (open)

(Abstract sent to MPS-SI/1 list)
FIG. 1 MAGNET CORE CONSTRUCTION
CERAMIC TUBE
INVAR CONNECTOR
COPPER TUBE

CERAMIC FEEDTHROUGH

SEPTUM CONDUCTORS \(3(30 \times 3)\) mm\(^2\)
INNER CONDUCTORS \(3(30 \times 6)\) mm\(^2\)

ALUMINA SUBSTRATE

ELECTRICAL CIRCUIT AND COOLING DIAGRAM

FIG. 2 THE 3-TURN SEPTUM COIL
A. INNER CONDUCTORS HELD TOGETHER WITH A CLIP
KAPTON INSULATION THROUGHOUT

B. INNER CONDUCTORS PRESSED TOGETHER WITH REINFORCED LONG SPRINGS
ALUMINIUM OXIDE INSULATION ON THE SEPTUM CONDUCTORS

FIG. 3 CONSTRUCTION OF THE 3-TURN COIL
FIG. 6 COMPARISON OF THE CALCULATED AND MESURED FLOW
**FIG. 7A** THE CALCULATED TEMPERATURES AT THE HOT END OF THE SEPTUM

**FIG. 7B** THE CALCULATED TEMPERATURES AS FUNCTION OF POSITION ALONG THE COIL BETWEEN 0 AND 0.5 SEC. FOR THE PULSES SHOWN IN FIG. 7A

\[
\begin{align*}
V &= 12 \text{ ms}^{-1} \\
Q_w &= 49 \text{ l m}^{-1} \\
t_p &= 0.4 \text{ s} \\
t_r &= 1.2 \text{ s} \\
I &= 11.3 \text{ kA}
\end{align*}
\]
A. THE FUNCTIONS $I(t)$ AND $[T_{cu}(t) - T_0]$ MEASURED AT THE HOT END OF THE 3-TURN SEPTUM (NEW)

B. THE FUNCTIONS $I(t)$ AND $[T_{cu}(t) - T_0]$ MEASURED AT THE HOT END OF THE 2-TURN SEPTUM (NEW)
A. THE FUNCTIONS $I(t)$ AND $[T_{cu}(t) - T_0]$ MEASURED AT THE HOT END OF THE 3-TURN SEPTUM AFTER 5 Ms.

B. THE MAXIMUM PULSELENGTH AS FUNCTION OF PULSE CURRENT

Fig. 9
FIG. 10. HEATING AND COOLING CURVES FOR 2 TYPES OF HEATERS
FIRST PUMP DOWN CURVE
1 HEAT IN AIR TO 160°C,
2 DRY N₂ FOR 2 HOURS,
3 DRY N₂ FOR 5 HOURS,
4 DRY N₂ FOR 15 MIN AND AIR
   FOR 2 HOURS, TANK OPEN,
5 AIR FOR 1 HOUR, TANK CLOSED.

CORE CONSTRUCTION
ALL LAMINATIONS PHOSPHATED
AND MOUNTED ON GIRDER, NO COIL

UNACCEPTABLE
REGION

ACCEPTABLE
REGION

FIG. 11 PUMPING CHARACTERISTICS FOR A PHOSPHATED CORE
FIG. 12 FIRST PUMP-DOWN CHARACTERISTICS OF THE VARIOUS CORE CONSTRUCTIONS
0. FIRST PUMP DOWN CURVE
1. HEAT IN AIR TO 180°C
2. DRY N₂ FOR 2 HOURS,
3. DRY N₂ FOR 10 MIN THEN
   EXPOSED TO AIR FOR 5 HOURS
   TANK OPEN,
4. AIR FOR 1 HOUR TANK CLOSED.

CORE CONSTRUCTION:
1. PHOSPHATED LAMINATION TO 5 BLANKS
2. CORE 715 mm LONG, ASSEMBLY WITHOUT
   GIRDER, NO COIL

FIG. 13 PUMPING CHARACTERISTICS FOR A DILUTED CORE
0 FIRST-PUMP DOWN
1 HEAT IN AIR TO 190°C
2 DRY N₂ FOR 2 HOURS
3 DRY N₂ FOR 10 MIN, THEN EXPOSED TO AIR FOR 5 HOURS TANK OPEN

CORE CONSTRUCTION
1 PHOSPHATED LAMINATION TO 6 BLANKS ASSEMBLY ON GIRDER, COIL WITH KAPTON INSULATION.

FIG. 14 PUMPING CHARACTERISTICS FOR A COMPLETE MAGNET
THICKNESS 0.5 mm
ANNEALED IN VACUUM
6 HOURS AT 1100°C
$H_c \approx 20 \text{ A m}^{-1}$

FIG. 15 THE MAGNETIC PROPERTIES OF HYPERM-4
FIG. 17 THE SHAPE OF THE END FIELD AND THE EQUIVALENT MAGNETIC LENGTH
Fig. 19 BLOCK DIAGRAM MAGNET PROTECTION
Fig. 20 CALCULATED BEAM LOSS DISTRIBUTION IN THE EXTRACTOR MAGNETS