A 200 KGAUSS PULSED MAGNET
FOR EMULSION EXPERIMENTS

E. Braunersreuther, J.C. Combe,
L. Hoffmann and M. Morpurgo.
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GENEVE
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I. INTRODUCTION

The design and construction of the CERN pulsed magnet apparatus has been reported briefly in CERN Report 60-27\(^1\). In the meantime, experience and measurements have suggested some improvements which will be described here.

The pulsed magnet (with different coils) has been designed as an apparatus essentially to be used for emulsion experiments. The main characteristics of the field required for a first step were:

i) fields of the order of 200 kgauss over a volume of about 40 cm\(^3\) needed for stacks of 2-3 cm thickness composed of circular pellets of an area between 30 and 50 cm\(^2\) perpendicular to the field;

ii) a variation of the field over the useful volume as small as possible, say lower than 3\%;

iii) a magnetic field almost constant during the time of a PS radiation burst.

The commonly applied method to obtain homogeneity of the field in coils is the use of a Helmholtz pair of coils. Condition ii) is then fulfilled by an appropriate geometry of the two half coils. The gap between the two coils can be used for holes such as, for example, those needed for beam passage. Point iii) means a relatively large value of the coil inductance (multi-turn coils).

In this report the results of measurements and calculations are discussed in the light of the above requirements. The constructional principles of the new coils and of the apparatus, and the recent changes, are reviewed.

In Refs. 2-9) is given a selection of the work done in this field in various laboratories.
II. EQUIPMENT, CIRCUITS, AND SWITCHING SYSTEM

1. Principle of operation and circuits

The pulsed magnet apparatus consists essentially of three parts, i.e., a condenser bank, a charging unit, and a coil. The principle of the operation can be described by considering the simplified circuit shown in Fig. 1. If switch 1 is closed, the condensers of the capacity, \( C \), will be charged. After seven seconds, the full voltage of 2.8 kV is reached. The charging operation can be stopped at any voltage up to 2.8 kV by presetting a voltage relay which triggers switch 1. The discharge of the capacitors through the coil of the inductance, \( L \), will be initiated by closing switch 2. With the present values of \( L, C \) and \( R_{AC} \) (where \( R_{AC} \) is the AC resistance of the discharging circuit), one would get a damped oscillation. To protect the condensers against the voltage backswing, switch 3 is closed just before the voltage changes the polarity (crowbar method). Figs. 2a and 2b show the voltage on the capacitors as function of time with and without the crowbar operation, respectively.

Figure 3 shows the circuit and the switching system in more detail. Each of the two switches, 1 and 2, consists of six ignitrons (PL 5555) in parallel. We have tested the apparatus up to a 120 kA peak current, corresponding to 20 kA for each igniton. We estimate that in our conditions 25 kA is a safe limit for each igniton. One unit used to trigger the six parallel ignitrons is shown in Fig. 4. The trigger unit 1 (Fig. 3) is operated by a 40 V pulse (1-2 \( \mu \)s) from the delay unit 1. The ignitrons B are triggered by the same pulse after an additional delay (delay and trigger unit 2) corresponding to the rise-time of the discharge current.

2. Charging unit

For charging the condensers we have used initially a commercial apparatus. A continuously variable autotransformer (driven by a motor) provided a nearly constant charging current. The autotransformer was followed by a high voltage transformer and silicon
rectifiers. A fault occurred in the sliding contacts of the auto-
transformer after about 10,000 operations. The continuous change
of the voltage had to be replaced by three fixed steps on the auto-
transformer. The current is now limited by a set of resistances.
Figure 5 shows the charging current and the condenser voltage as a
function of time. A basic diagram of the modified charging circuit
is given in Fig. 6. Interlocks protect all devices which require
cooling, such as ignitrons, resistances, and the coil. A special
interlock prevents the start of the charging operation when the
capacitor voltage is more than 50 V. This might happen when the
condensers have not been completely discharged during a previous
misoperation.

3. Condensers

The 30-ton capacitor bank has been mounted on a trailer
together with the charging unit (Fig. 7). This enables the con-
denser bank to be placed in the experimental areas of the FS near
to the coil without having too long connections. The capacity of
the 250 condensers in the bank is 75,000 \( \mu \)F. At the maximum charging
voltage of 2.8 kV, the stored energy is 300,000 joule. Further de-
tails of the condenser bank are given in reference 1).

III. COILS

Table I shows the mechanical and electrical characteris-
tics of the different coils which have been constructed.

1. Electrical characteristics

The electrical characteristics of the coil (inductance \( L \)
and AC-resistance \( R \)) can be measured using a free oscillating LC
circuit. The oscillogram in Fig. 2b shows the voltage across the
coil as a function of time. \( U_0 \) is the maximum voltage at the time
\( T = 0 \), immediately after closing off the discharge circuit. \( U \) is
<table>
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<tr>
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<th>CONDUCTOR</th>
<th>GEOMETRY</th>
<th>MATERIAL</th>
<th>THICKNESS (mm)</th>
<th>INSULATION</th>
<th>THICKNESS (mm)</th>
<th>Type</th>
<th>Notes</th>
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<tr>
<td>Ia</td>
<td>Cu (soldered)</td>
<td>Ia</td>
<td>Cu</td>
<td>0.2</td>
<td>15</td>
<td>Vetonite</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ib</td>
<td>Cu Be (1%) (soldered)</td>
<td>Ib</td>
<td>Cu Be</td>
<td>0.2</td>
<td>15</td>
<td>Vetonite</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Cu Cr (silver-soldered)</td>
<td>II</td>
<td>Cu Cr</td>
<td>0.4</td>
<td>20</td>
<td>Vetonite</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Cu Cr (silver-soldered)</td>
<td>III</td>
<td>Cu Cr</td>
<td>0.4</td>
<td>20</td>
<td>Vetonite</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Table I
- For Table I, see Fig. 19.
- (1%) Be refers to 1% beryllium addition to copper.
- (1%) Cr refers to 1% chromium addition to copper.
- (Silver-soldered) refers to the use of silver-soldered connections.

**Formula:**

$$E = \frac{V}{2000}$$

**References:**
- **References:**
- **Figures:**
- **Tables:**
- **Notes:**

**Material:**
- Cu: Copper
- Cu Be: Copper with 1% Be addition
- Cu Cr: Copper with 1% Cr addition
- Vetonite: Veticulite

**Thickness:**
- Thickness values in millimeters (mm)

**Geometry:**
- Ia, Ib, II, III

**Type:**
- Cu (soldered)
- Cu Be (1%)
- Cu Cr (silver-soldered)

**Electrical Properties:**
- PEAK FIELD (Hc)
- MAX. CURRENT (Ia)
- For peak field (Hc)

**Table I**
the voltage of the first inverse peak of the oscillation (= maximum backswing) after a half-period $T/2$. The oscillogram gives $U/U_0$ and $T/2$. The capacity of the condensers $C$ is known. Therefore, the inductance $L$ and the AC-resistance $R$ can be easily calculated using the following two equations:

$$\frac{U}{U_0} = e^{-\frac{NT}{4L}}$$  \hspace{1cm} (1)$$

and

$$\frac{T}{2} = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}$$  \hspace{1cm} (2)$$

The larger inductance of coil Ib (compared to coil Ia which has the same geometry) results from the different skin depths in Beryllium and Copper. The skin depth is proportional to the square root of the specific resistance of the conductors\textsuperscript{1).} Coils Ia and II both have copper as conductor, with the same number of turns and the same inner diameter. They differ only by the radial thickness of the conductor, which is 2.5 times smaller in coil II. The small increase of the AC-resistance as well as the smaller inductance of coil II indicates a current distribution with a mean current path at a smaller radius than for coil Ia. This suggests a current distribution with a mean value slightly deeper in the conductor than expected from the skin depth. The measurements of $R_{AC}$, for all coils measured, are smaller than expected from calculations, also indicating a larger skin depth of the current.

The DC-resistance $R_{DC}$ was directly measured using a DC-current. The peak current in the case of coils Ia and Ib has been evaluated by measuring the magnetic field of the known geometrical configuration between the connection bars. The result agreed with the calculation using $R_{AC}$ and $L$ determined by the oscillograms and Eq. (6). The values of the current for the other coils were then only calculated with the last method.
The current of a damped oscillation is given by the integral of
\[ L \frac{d^2 q}{dt^2} + R \frac{dq}{dL} + \frac{1}{C} q = 0 \]  
(3)
(q = charge at the condenser at the time "t") with the solution
\[ \frac{dq}{dt} = \omega \frac{q_0}{\sqrt{LC}} \left\{ \omega \cos (\omega t + \delta) - \frac{R}{2L} \sin (\omega t + \delta) \right\} e^{-\frac{Rt}{2L}} \]  
(4)
where \( q_0 = C \cdot U \) (\( U \) = voltage across the condensers at \( t = 0 \)), and
\( \omega = \left( \frac{1}{LC} - \frac{R^2}{4L^2} \right)^{1/2} \).

The peak current is reached if \( \omega t = \delta \) with \( \delta \) given by
\[ \tan \delta = \frac{2\omega L}{R} \]  
(5)
and the maximum value of the current is then
\[ I_{\text{max}} = U_0 \sqrt{\frac{C}{L}} e^{-\frac{R t(\delta)}{2L}} \]  
(6)
where \( U_0 \) = maximum voltage across the coil, and
\( t(\delta) \) corresponds to the time \( t = \delta / \omega \).

The variation of the current in time is indicated by the variation of the field in time. But the field shape can be measured easily using the Hall effect (Section V).

The Hall pulsed oscillogram (Fig. 8) gives therefore an additional information, as the peak value of the pulse is reached after the time \( t(\delta) \).

The efficiency \( \eta \), indicated in Table I, is defined by the ratio between the maximum magnetic energy stored in the coil and the initial energy stored in the condensers,
\[ \eta = \frac{\frac{1}{2} L I_{\text{max}}^2}{\frac{1}{2} C U_0^2} \]  
(7)
Using the relation (6) we get
\[ \eta = \left( \frac{U_0}{U} \right)^2 e^{-\frac{R}{L} t(\delta)} \]  
(8)
The exponent of the e-function demonstrates the influence of the values \( R/L \) and \( t(\delta) = \delta/\omega \), where \( \delta \) is given in Eq. (5).

The factor \((U_0/U_c)^2\) depends on the losses in the ignitrons and on the inductance of the connections. The ratio of voltage measured across the coil and across the condensers \((U_0/U_c)\) is larger than 0.9 for voltages of 1 to 2 kV, using connections of 12 to 15 metres. Instead of connection bars as described in Ref. 1 we now use six flexible coaxial cables in parallel. The copper cross-section of one cable is \(2 \times 120 \text{ mm}^2\). The inductance of the 15 m line is less than 0.2 \(\mu\text{H}\) and the DC-resistance approximately \(0.4 \Omega\).

2. Details of new coils

The type I coil has already been described in Ref. 1. Coil Ib is identical to Ia, but made of Beryllco instead of commercial copper (Coil Ia). However, this material has a large electrical resistivity compared to copper. Therefore, the damping is high [Eq. (6)] and this material is not recommended for pulses of a few milliseconds length as used in our case. Table II shows the properties of different materials used as conductor.

<table>
<thead>
<tr>
<th></th>
<th>Relative resistivity*</th>
<th>Relative strength*</th>
<th>Annealing temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (commercial)</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Copper (1%) Chromium</td>
<td>1.1</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td>Copper (1.7%) Beryllium</td>
<td>2.8</td>
<td>3-4</td>
<td>225</td>
</tr>
<tr>
<td>Copper (2%) Beryllium</td>
<td>3.3</td>
<td>4-5</td>
<td>225</td>
</tr>
</tbody>
</table>

*) The values refer to room temperature.
For coil III (Figs. 9 and 10) we have used Copper Chromium (1% Cr) as conductor, which has higher strength compared to copper with negligible increase of the electrical resistance. The construction was similar to that of coil I, but coil III has a larger inside and outside diameter. The discs were hard soldered. Vetronite (glass fibre impregnated with epoxy resin) was used for insulation. The whole coil was impregnated in vacuum with epoxy resin. The inside surface of the coil was machined and treated electrolytically after impregnation. The result is that the insulation protrudes a few tenths of a millimetre with respect to the copper. This procedure should decrease the risk of flashover. The frame (Fig. 10) consists of two stainless steel blocks to pre-compress the coil axially. Radial stresses are supported by a number of stainless steel rings fitted on the Vetronite cylinder of the coil (Figs. 9a and 9b). The single ring is radially splitted to avoid eddy currents. All rings are insulated and glued together taking care that the radial cuts are shifted in angle, each with respect to the other. Therefore, this cylinder of rings has almost the same mechanical resistance as a massive cylinder without having a closed loop.

Coil II (Fig. 11) consists of a spiral made by bending a tape without any joints. The helix and the interleaved insulations are compressed and impregnated in a stainless steel container which replaces the axial frame. The radial frame consists of stainless steel rings as for coil III. The coil (with frame) is much smaller than the other types, but the smaller copper volume is a disadvantage as far as the heat capacity of the coil is concerned.

Until now, coil II has been pulsed about 600 times, and coil III about 1,200 times at a field of between 150 and 200 kgauss. At present the conditions of both coils seem to be very good.
A further coil (coil IV) has been designed and is under construction. The conductor consists of 2 mm thick rectangular plates of CuCr (20 × 40 cm²). The split plates are soldered to form a helix. The two half coils (2 × 15 turns) are connected by a 2 cm thick copper-turn of the same area as the plates. As insulation we use two overlapping leaves of teflon fibre. The inside dimensions of the coil are 12.5 cm × 4.5 cm. Two stainless steel plates compress the coil in the axial direction, and two further plates support the stresses in direction perpendicular to the long side of the coil. The large size of the plates provides the necessary rigidity in the other direction and the large volume of the Copper Chromium gives a good heat capacity.

This coil with a long transversal field is designed for experiments which require a long path of particles in a high field (150-180 kgauss). In the thick copper conductor between the two half coils are holes for the beam of 1 cm diameter.

3. Cooling

The coils are cooled by a stream of fluid circulating between a plexiglas cylinder and the inside surface of the coil. About 30 litres of fluid are needed to fill the cooling circuit. The fluid itself is cooled by passing through a heat exchanger.

The transformer oil which was first employed as cooling fluid does not allow a high repetition rate to be used, as the temperature is limited by the quality of the araldite and must be kept lower than 80°C. The cooling with demineralised water, which we now use, is far more effective. Fig. 12a shows the temperature rise Δt as function of time for water and oil cooling respectively, using different repetition rates and fields. The average copper temperature was measured by variation of the DC-resistance of the coil. After about 100-150 pulses the temperature reaches an equilibrium.
Figure 12b shows the temperature rise in the Copper and in the Vetronite. As expected, the rise of the temperature in Copper is faster than in the Vetronite, as also the drop of the temperature after pulsing. The temperature in the Vetronite was measured with a Thermistor (PTC-resistance) in a thermoinsulated hole of the Vetronite between the two half copper coils.

The temperature in the useful volume inside the plexiglas cylinder can be kept always lower than 24°C, the exact value depending on the temperature of the room as well as on the temperature of the cooling water in the heat exchanger.

IV. TIMING

1. Pulse length

The length of the field pulse is determined by the fact that the field should vary less than 2% during a time interval corresponding to the half width of the shortest radiation burst which can be obtained from the FS, which is of the order of 300 µs. The variation in time of the field pulse depends on two characteristics:

i) the period of the oscillation (Eq. 2); and

ii) the ratio $R/L$ which determines the damping (Eq. 4).

The change of the field in the time interval $\Delta t$ around the peak value of the field at the time $t_m$ follows from Eqs. (4) and (6). The field at the time $t = t_m \pm \Delta t$ with respect to peak value at $t_m$ is then given by

$$\frac{H(t)}{H(t_m)} = \left\{ \cos (\omega t + \delta) - \frac{R}{2\omega L} \sin (\omega t + \delta) \right\} e^{-\frac{R}{2L}(\pm \Delta t)} \quad (9)$$

where $t = t_m \pm \Delta t$.

For example, for coil III the field is 1.5% smaller at $t_m \pm 150 \mu s$ than its maximum value at $t_m$. 

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2. Synchronization

The maximum field for the coils I-III is reached 2-3 msec (2.15 msec for coil III) after triggering. A triggering pulse from the PS machine (given a few msec before the beam hits the target) is delayed by the adjustable delay unit 1, so that the peak of the field and the peak of the burst coincide. Figure 13 shows the synchronization of a proton burst and a field pulse on the same time scale.

V. MEASUREMENTS OF THE MAGNETIC FIELD

1. Principle

The Hall effect was used to measure the peak field and the field shape as a function of time. The independence of the Hall constant $R_H$ with respect to the magnitude of the field was checked for fields up to 160 kgauss for the semi-conductors In As and In (As$_{0.8}$P$_{0.2}$)$_1$. So also for high magnetic fields the following equation can be used:

$$U_H = \frac{R_H}{d} I_c B$$

(10)

where:
- $U_H$ = Hall voltage for open circuit
- $R_H$ = Hall constant
- $I_c$ = control current
- $B$ = magnetic induction
- $d$ = thickness of the Hall plate.

In practice, the connections to the Hall plate form a loop with an area $A$, so an additional voltage $u_i$ might be induced by the magnetic field and the measured voltage becomes:

$$U_H + u_i = \frac{R_H}{d} I_c B + A \frac{dB}{dt}$$

(11)

In addition to that, the conductivity $\sigma$ of the semi-conductor changes
with the magnetic field according to the following relation:

$$\frac{\sigma(0)}{\sigma(B)} \approx 1 + a \cdot B^2. \tag{12}$$

For both semi-conductors n is \(\approx 1.5\). The ratio \(\sigma(B)/\sigma(0)\) drops at 180 kgauss by a factor 8 for In As and by a factor 3.3 for In As P.

The circuit for measuring the field is shown in Fig. 14. The voltage is measured with an oscillograph. A stabilized voltage source supplies the control current \(I_0\) through a high resistance \(R\). This resistance \(R\) in the Hall current circuit has to be large compared to the variation of the resistance of the Hall plate in the field [Eq. (12)].

The error, which is connected with \(u_1\), can be determined by the measurement of the inductance component \(A \frac{dB}{dt}\) in the pulsed field for the Hall control current \(I_0 = 0\).

A compensation of the inductive component is possible by means of an appropriate small loop in the pulsed field connected in series of the Hall voltage circuit. Figure 15 shows the Hall voltage as well as the inductive component as a function of time. In this case, no compensation was needed because the induced voltage \(u_1\) was so small that one could neglect it.

The Hall plate has been calibrated by comparing the Hall voltage with the induced voltage in a small solenoid of known dimensions. Figure 16 shows the Hall signal and the induced voltage in the solenoid as a function of the time. By integration of the induced voltage in the solenoid one obtains the corresponding shape of the Hall voltage pulse.

2. Field distributions

The distribution of the field was measured in the volume of a coil as well as outside. Here, only the peak of the Hall pulse is of interest. At the peak field is \(\frac{dB}{dt} = 0\), so the inductive component \(u_1\) is without any influence.
To eliminate variations related to the charge of the condenser bank, a second Hall plate was used as a reference plate at a fixed place inside the coil. Figures 17a and 17b show the field of coil I in the \(z\) - and \(r\)-direction, respectively. Figures 17c and 17d show the field pattern inside the volume of the coil I. Figures 18 a-c give the corresponding results for coil III. It should be mentioned that all data correspond to the field component in the axial direction.

The field distribution along the axis of the coil can be calculated from the geometrical configuration of the coil and is given by:

\[
\frac{B_{\text{max}}(z)}{B_{\text{centre}}} = \frac{(\cos \alpha_1 - \cos \alpha_2) + (\cos \alpha_3 - \cos \alpha_4)}{\frac{2l}{\sqrt{r^2 + l^2}} - \frac{b}{\sqrt{r^2 + b^2/4}}} \tag{13}
\]

(for the geometrical notations, see Fig. 19).

The field in the centre of the coil is given by:

\[
B_{\text{centre}} = \mu_0 \ U_0 \ \frac{\sqrt{C}}{L} \ e^{-Rt(\delta)/2L} \ n \ \frac{2l}{\sqrt{r^2 + l^2}} \ \frac{b}{\sqrt{r^2 + b^2/4}} \tag{14}
\]

using \(I_{\text{max}}\) from Eq. (6),

\(\mu_0 = 1,256\) and \(B\) in gauss,

\(n\) = number of turns per cm.

The calculated field distribution along the axis agrees with the measured values assuming for the calculation that the current is concentrated in a circular path of a radius \(r\) slightly larger than the geometrical inside radius \(r_0\). For coil III, for example, we found \(r = r_0 + 4\) mm corresponding to depths slightly deeper than a half skin depth \(\delta^*)\) measured from the inner surface.

\(\delta^*)\) The expected skin depth \(\delta\) is proportional to \(\sqrt{\rho T}\) (where \(T\) = period of oscillation and \(\rho\) = resistivity) for \(\delta < \text{radial conductor thickness}\) [see Ref. 1]. \(\delta\) is about 6.5 mm for coil III.
VI. FURTHER POSSIBLE IMPROVEMENTS

1. Use of higher fields and single-turn coils for emulsion experiments

The use of magnetic fields higher than 200 kgauss has several important advantages for experiments with emulsions inside the coil, for example, for momentum measurements on tracks or especially in the case of measurements on particles of short lifetime.

The accuracy of curvature measurements in emulsions is strongly dependent on the ratio between the magnetic deviation angle $\theta_m$ and the mean angle of multiple scattering $\theta_S$. This ratio is given by:

$$\frac{\theta_m}{\theta_S} \approx 6 \cdot 10^{-5} B \beta \sqrt{t}$$

(B in gauss, $t =$ cell length $\leq \frac{1}{2}$ track length in cm).

$\theta_m/\theta_s$ is about 12 for $B = 200$ kgauss and $t = 1$ cm assuming $\beta = 1$. With this value of $\theta_m/\theta_S$, momentum measurements of 12-24 GeV/c particles are possible with an accuracy of $\pm 10\%$ (standard error)\(^{11}\). In practice, it is important to be able to measure short track lengths. The pellicles used till now have a diameter of 6-7 cm, but in many cases dipping tracks have a too short length in a single 600 $\mu$m pellicle. Therefore, it would be very valuable to have higher fields and to keep to the accuracy given by $\theta_m/\theta_S$ also for short tracks with a small $t$. For example, a field of 400 kgauss is needed for a track of 5 mm length (measured on two cells $t = 2.5$ mm), if $\theta_m/\theta_S = 12$ is required.

For low-energy particles ($\beta \ll 1$), the field $B$ is again the most useful parameter to be increased if $\theta_m/\theta_S$ should be kept as high as possible.

Higher fields are extremely useful for momentum separation and magnetic analysis of short-lived particles in order to have an appreciable bending of the particles over a short path. Particularly in the measurements of the magnetic momentum of hyperons, high fields are required to get a large precession angle of the spin over a short range.
The production of pulsed fields higher than the order of 200 kgauss, over the volumes considered, is much facilitated by the construction of single-turn coils. Coils of this type can be made mechanically stronger and so larger electromagnetic forces can be supported. Moreover, with single-turn coils, it is possible to have more complicated geometrical configurations, and larger holes in the conductor can be made for placing emulsions near to the high field but outside the beam path. This geometry is useful for the momentum separation of particles.

Generally, single-turn coils (with an inductance of less than \( \frac{1}{10} \mu \text{H} \)) are used for very short pulses in time. This type of coil would not be useful in connection with the existing short particle burst of about half a millisecond, as it is now at the FS. The fast ejected proton beam of 0.1 to 2 \( \mu \text{s} \) burst length (foreseen for the end of 1962) would have a convenient length for a coil of this type. But on the other hand, for very short pulse lengths a strong limitation is given by the resonance frequency of the condensers, which in our case is 20 kHz. Furthermore, for the very high currents the switching system had to be extended.

A single-turn coil with our existing equipment would require the use of a current transformer. From the point of view of mechanical strength one could probably produce fields up to 400 kgauss. The maximum useful volume is, of course, related to the available stored energy.

2. Pulsed transformer

The equivalent circuit of the current transformer is shown in Fig. 20. The following conditions would be required: \( L_n \ll L, R_1 \ll R, L_2 \gg L \), and \( R_2 \) must be large. A transformer fulfilling these conditions could be constructed according to the following principle: primary and secondary windings of the transformer would consist of a number of interleaved copper discs separated by sheets of insulation. The primary discs would all be connected in series.
while the secondary discs would all be connected in parallel. As energy dissipation we assume 50 kilojoule per pulse.

3. Flux Concentrator Coil

A commonly applied method\textsuperscript{1,2} to obtain higher fields by short pulse lengths is the use of flux concentrators. The principle of a single turn coil and a pulsed transformer could be combined as illustrated in Fig. 21. The secondary winding of the pulsed transformer consists of a single turn coil (a slotted copper cylinder). The primary coil (essentially a helix of a few insulated turns) fits from outside in the helical thread of the secondary single turn block. The current induced in the single turn cylinder can be concentrated using an appropriate inside geometry.

4. Sweeping Coil

This arrangement consists of two coils connected in series. The first coil (sweeping coil) could be used to bend a part of the beam into the second coil (working coil). The two coils could be made of a few turns. The energy spent in the sweeping coil should not be more than 20\% of the total energy. The advantages of this two-coil system would be:

i) the independence of the burst length;

ii) the synchronization of burst and field pulse is automatically given. No particle will reach the working coil if the field has not the right value. This interlock system does not exist otherwise.

iii) the shorter field pulses required will make it possible to use coils with fewer turns, which can be made mechanically stronger and probably stand higher fields.

The geometrical arrangement could be made in two different ways: the distance of the two coils as short as possible, or very large (distance in the order of 10 m). In the first case a hole is
foreseen in the working magnet for the undeflected beam; in the second case, a collimator could provide that the undeflected beam does not hit the frame of the working coil.

All these improvements have been discussed from the point of view of the existing equipment, without regard to changes due to very fast condensers or to cryogenic coils.

*

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2876/WP/kw
Fig. 1
Simplified principle circuit

Fig. 3.

One part of the condenser bank and switching system. Two other parts are parallel to this part.
Fig. 2a. Voltage across the coil as function of time (with crowbar operation).

Fig. 2b. Voltage across the coil as function of time (without crowbar operation).

Fig. 8. Field pulse without crowbar operation. The peak value is reached after the time $t(\delta)$.

Fig. 15. Field pulse synchronized with the proton burst. The heights in arbitrary units. The base in msec.

Fig. 15. Hall pulse and induced voltage in a small solenoid for the calibration of the Hall generator by high fields.

Fig. 16. Hall pulse and inductive component.
Fig. 4. Trigger circuit
Fig. 5. Voltage and current as function of time during the charging operation.
Fig. 6.
Basic diagram of the charging unit
Fig. 7. The condenser bank. The six parts of the bank with the six ignitrons in parallel can be seen. The second row of ignitrons below are the crowbar switches (partly behind the HV transformer).

Figs. 9a and 9b. Coil III with the radial frame of slotted stainless steel rings. The inside diameter is 7.2 cm.
Fig. 10. Coil III with frame.

Fig. 11. Coil II. The outside diameter with the frame of stainless steel rings is 24 cm, the inside diameter 5 cm.
Fig. 12a. Temperature increase in the copper as function of the pulse number.

- watercooling $11/\min$ repetition rate 6" 200 kgauss
- oilcooling $4.5/\min$ 12" 100 kgauss
- " " 18" 100 kgauss

Fig. 12b. Temperature rise and drop in the conductor and in the insulation vs. pulse number (18th repetition). Interruption after 27 pulses.

- Temperature in Cu
- " " in vetronite
Fig. 14. Circuit for the field measurements.
Fig. 17a-b
Axial and radial field distribution of coil Ia.

Fig. 17c
Field distribution in the inside volume of coil Ia as function of r, and z as parameter.
Fig. 18 a-c
Axial and radial field distribution of coil III.
Fig. 19.
Section through a coil.
The broken line represents the average current path.

Fig. 20.
Equivalent circuit of a current transformer

Fig. 21.
Principle of a pulsed transformer coil.
(with flux concentrator)