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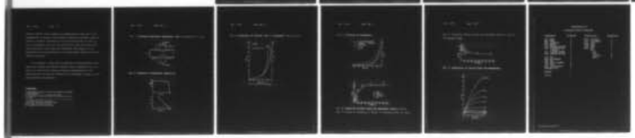

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PRODUCTION OF ULTRAHIGH MAGNETIC FIELDS

by

Hemio Latal

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PRODUCTION OF ULTRAHIGH MAGNETIC FIELDS* **

Heimo Latal

Institute for Theoretical Physics of the University of Graz

(With 7 figures)

[FOOTNOTE: * Lecture presented at the Autumn Conference of the Austrian Physics Society in Inssbruck, 1967. END FOOTNOTE]

[FOOTNOTE: ** This work was supported by the U. S. Army Research Office (Durham). END FOOTNOTE]

By the development of an implosion method a group headed by C. M. Fowler in Los Alamos [1] succeeded in obtaining short-term magnetic fields of several megagauss (MG). A conducting cylindrical metal tube, the so-called liner, was radially compressed by a high explosive following which an initial field on the order of 50 kG was produced in the cavity using a Helmholtz coil (Fig. 1). The highest field strengths attained with this method are around 15 MG and a Russian group [2] gives 25 MG.

The principle of this "flux compression" [3] can be illustrated in the following manner: the change of the magnetic flux brought about by the inward-moving cylinder walls, according to Faraday, produces supplementary currents which as a result of their forward direction effect an increase in the original magnetic field and thereby convert mechanical energy into magnetic energy. Under the simplest assumptions of a constant specific resistance differing from zero ρ_0 and constant velocity v_0 of the implosion, using Faraday's law one obtains

$$-\frac{d\Phi}{dt} = iR, \tag{1}$$

the growth of the magnetic field with decreasing radius of the liner according to (Theory A)

(A)
$$\frac{B}{B_0} = \left(\frac{r_0}{r}\right)^{2(1-\alpha_0)}.$$

Here B_0 and r_0 are the initial field and the initial radius, respectively, while α_0 is given by

(2)
$$\alpha_0 = \frac{\varrho_0}{\mu_0 \delta_0 v_0},$$

in which value δ_0 designates a characteristic penetration depth for the calculation of the electrical resistance (R).

Since the magnetic field exerts a pressure on the conducting walls surrounding it (proportional to B^2) the velocity of the liner walls will not remain constant. Fig. 2 shows the result of calculations which take this effect into account (Theory B). One sees that in the last tenth of the compression considerable deviations from uniform movement arise which lead to an end radius, the so-called "turn-around radius" which differs from zero. The limitation of the investigations to the first nine tenths of the compression therefore justifies the assumption of a constant velocity.

Other factors also exist, however, which limit the size of the maximumly attainable fieldstrengths. Thus one must take into consideration the fact that the magnetic field penetrates the walls surrounding it and thus part of it is lost for compression. If for simplicity one assumes a linear drop of the field in the walls within a certain penetration depth δ_0 then one obtains the following expression for the increase of the field (Theory C)

$$\text{(C)} \qquad \frac{B}{B_0} = \left[\frac{r_0^2 + r_0\delta_0 + \delta_0^2/3}{r^2 + r\delta_0 + \delta_0^2/3}\right]^{1-\alpha_0},$$

whereby α_0 is given by (2) and the characteristic penetration depth δ_0 (from other calculations [3]) is defined as

$$\text{(3)} \qquad \delta_0 = \left(\frac{\varrho_0 r_0}{\mu_0 v_0}\right)^{1/2} = \alpha_0 r_0$$

An additional important effect lies in the fact that the specific resistance of the liner is dependent on temperature. The assumption of a linear temperature increase according to the resistance

$$\text{(4)} \qquad \varrho = \varrho_0[1 + k(T - T_0)],$$

which expression can correspondingly be rewritten as a dependence of the magnetic field

(5)
$$\varrho = \varrho_0\left[1 + \beta\frac{B^2}{K^2}\right]; \quad K = \left(\frac{2\mu_0 c_v}{k}\right)^{1/2} \simeq 0{,}6\,\mathrm{MG}, \quad \beta \simeq 0.8,$$

leads to (Theory D)

(D)
$$\frac{B}{B_0} = \left[\frac{r_0^2 + r_0\delta + \delta^2/3}{r^2 + r\delta + \delta^2/3}\right]^{1-\alpha},$$

whereby

(6)
$$\alpha = \alpha_0\frac{1 + \beta(B^2/K^2)}{1 + \frac{B}{K}}, \quad \delta = \delta_0\left(1 + \frac{B}{K}\right).$$

As is known an applied magnetic field effects an increase of the resistance of metals ("magnetoresistance") and this effect can be taken into account simply by a change of β in (5) to a $\beta_m \simeq$ 2.5 β (Theory E).

For a certain "standard configuration" (S.C.) given by the following values of the different parameters:

Initial field $B_0 = 25$ kG

Initial radius $r_0 = 5$ cm

Initial velocity $v_0 = 5$ mm/μs,

Initial resistance $\rho_0 = 10$ μΩ-cm

Compression time $t_c = 10$ μs

Fig. 3 shows a comparison of Theories A to E. Here the enlargement factor B/B_0 as well as the field itself are plotted as a function of decreasing liner radius. Analysis of the results shows that one can define a "Region I" in which a magnetic field of ca. 1 MG is attained and the liner is compressed to a radius of approximately 7 mm. In this range the results are largely independent of the details of the various theoretical assumptions; in particular Theories A, B, and C cannot be distinguished. In the following "Region II" which reaches up to ca. 3 MG with a radius of 4 mm the experiments can lead to a choice among the various theorems. For the last stages of the implosion where the liner material is under a magnetic pressure of ca. 1 million atmospheres and the surface temperatures are several tens of thousands of degrees it is doubtful whether an extrapolation of the preceding results can be valid. Here, new effects could greatly change the definition of an effective resistance which is material for the description of the process.

By variation of the specific parameters such as specific resistance, implosion velocity, and initial magnetic energy a study was made of the extent to which the results, at least in region II lend themselves to improvement. Fig. 4 shows the result of this investigation: it is clear that increased velocity as well as lower resistance lead to higher fields. The most important result, however, arises from the fact that with an increase of the initial magnetic energy it is more advantageous to increase the volume than to raise the magnetic field.

Precisely the criteria which provide for a good compression (essentially $\rho_0 \simeq 0$), prevent, however, the production of a high initial field, one of the basic prerequisites for attaining ultrahigh fields, through the same mechanism: the initial field is produced by a capacitor discharge into a Helmholtz coil which is wrapped around the liner; thus currents are induced in the cylinder wall which reduce the field in the cavity, all the more so the better conductor the liner. Extensive calculations and experiments [4] have led to a complete description of this process, the results of which are shown in the following figures. Fig. 5 shows the variation of the maximumly obtainable field with the thickness and the specific resistance of the liner, while Fig. 6 shows the dependence of the point in time when the field is attained on the same parameters. The precise knowledge of this point in time is of decisive importance for the synchronization of the following implosion since shortly before attaining the maximum initial field the detonators must be ignited.

In order to see how the already mentioned contradictory conditions for the optimum production of the initial field and for the compression affect the end result of a total experiment, the variation of the maximum initial field with a specific resistance of the liner was calculated for a pre-assigned geometry and capacitor bank energy and then these values were substituted in Theory D for the compression. One sees in Fig. 7 that up to a compression radius of approximately 2 mm the optimum production of the initial field dominates, thus liners with high resistance (large initial field) yield ever larger compressed fields although the initial factor has reduced from 8 to 1.3. For even smaller radii, however, both effects almost counterbalance each other and the obtained field is more or less independent of the resistance of the liner.

A very interesting version of the implosion method which requires no explosive was developed by C. E. Cnare [5], electromagnetic compression (Cnare effect). Here a capacitor bank is discharged into a single-turn coil which is lined with thin foil (aluminum). The primary current and the almost equally large but opposite induced secondary current in the foil repel each other so that as a result of the mechanical asymmetry (massive primary coil, light foil) the foil is imploded. It is significant that through an appropriate choice of the system parameters part of the magnetic field originally between the primary and seconary winding can be diffused through the foil and then compressed. With a 130-kJ, 20-kV capacitor bank Cnare reached 2 MG follwing an 18-μs implosion time, and the foil was compressed from an initial radius of 25 mm to a final radius of 2 mm. A detailed theoretical investigation of this process [6], in addition to other important results, gave the following for the maximum value of the compressed magnetic field

$$B_m = \frac{\mu_0^2}{2\sqrt{7}} \frac{V r_0 d}{L_1 \varrho} \left(r_p^2 + \frac{l_p^2}{4} \right)^{-1/2} , \tag{7}$$

with the following designations:

V initial voltage on the capacitor,

L_1 inductivity of the primary circuit,

$r_p (\cong r_0)$ initial radius of the primary coil ($\cong$ the initial radius of the foil),

l_p length of the primary coil,

d initial thickness of the foil,

ρ specific resistance of the foil.

Although electromagnetic compression does not lead to such high fields as the explosive method (a suitable combination of both could resolve this, however) it does provide ultrahigh magnetic fields, without too much expenditure and destruction which are sufficient for the following applications which will be mentioned briefly.

From the number of areas in which the application of ultrahigh magnetic fields can lead to new interesting results, as for example solid state physics, plasma physics, quantum electrodynamics, let us select the latter. Here there are the high-energy electromagnetic transformation processes such as magnetic bremsstrahlung (synchrotron radiation), pair formation, etc. which acquire increased significance in these high magnetic fields. The appearance of strong radiation reaction effects during magnetic bremsstrahlung is only one of the consequences of quantum electrodynamic effects in ultrahigh magnetic fields; a detailed discussion of the new situation can be found in [7]. A fundamental study of this problem from both the theoretical and experimental sides seems very desirable with respect to its significance for understanding the electromagnetic interaction under extreme conditions.

In conclusion I would like particularly to thank Professor Paul Urban who, through his generous support, made it possible for me to carry out these works; likewise Professor Thomas Erber for his hospitality at the Illinois Institute of Technology, Chicago, and for many worthwhile discussions.

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Fig. 1. Implosion experiment (schematic). KEY: 1) Explosive; 2) Coil.

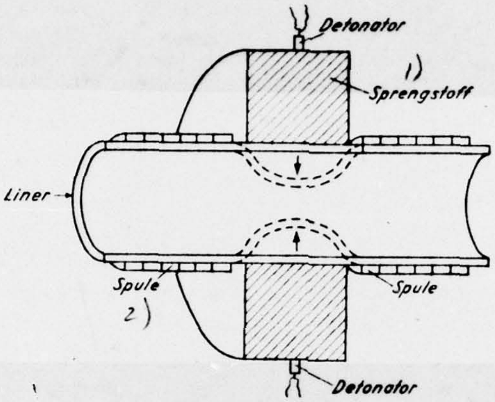


Fig. 2. Dynamics of compression (Theory B).

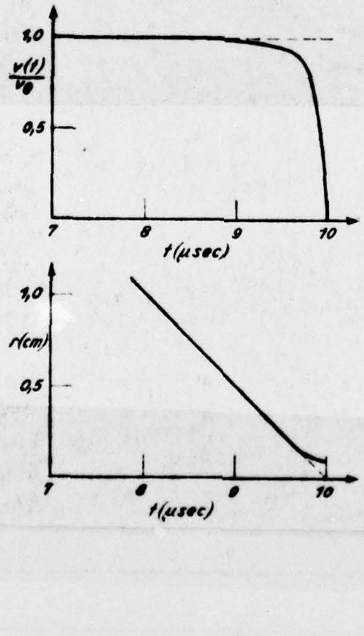


Fig. 3. Comparison of theories. KEY: 1) Compression time ≅ 10 μs.

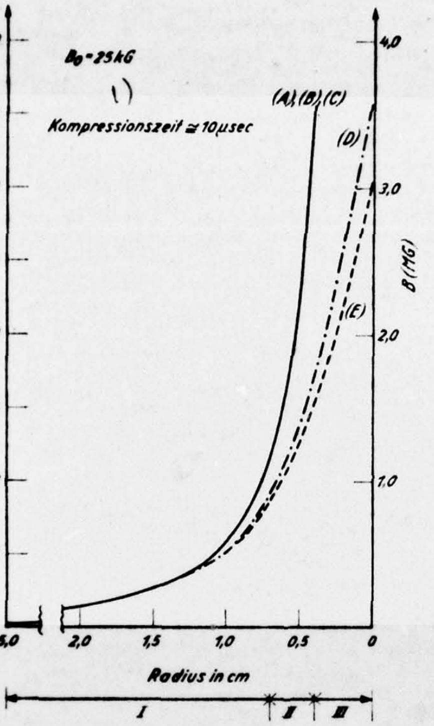
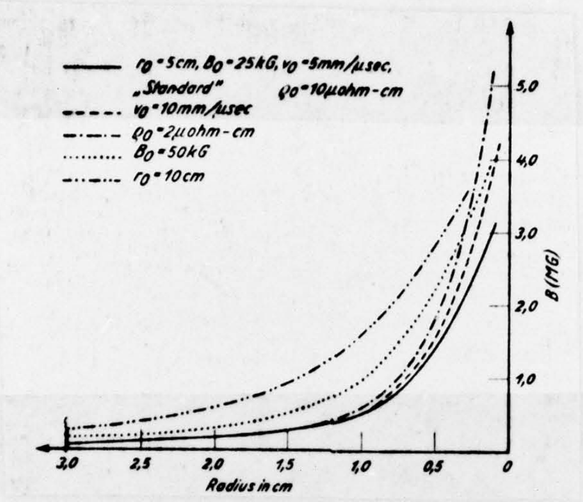


Fig. 4. Variation of parameters.



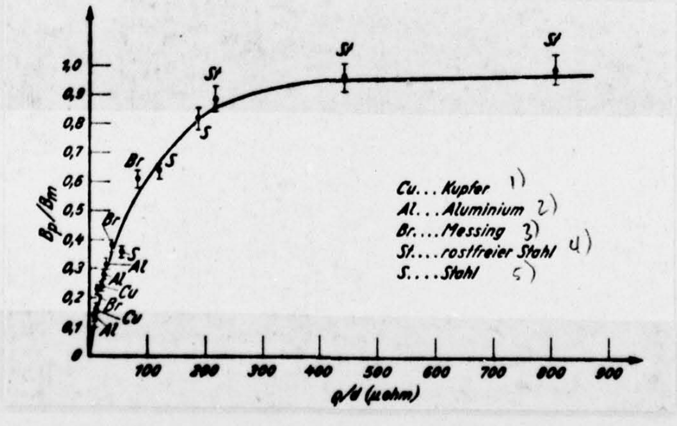


Fig. 5. Comparison between theory and experiment (maximum field).

KEY: 1) Copper; 2) Aluminum; 3) Brass; 4) Stainless steel; 5) Steel.

Fig. 6. Comparison between theory and experiment (point in time of the maximum field).

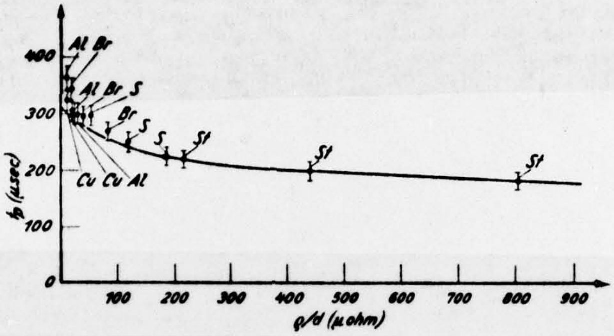
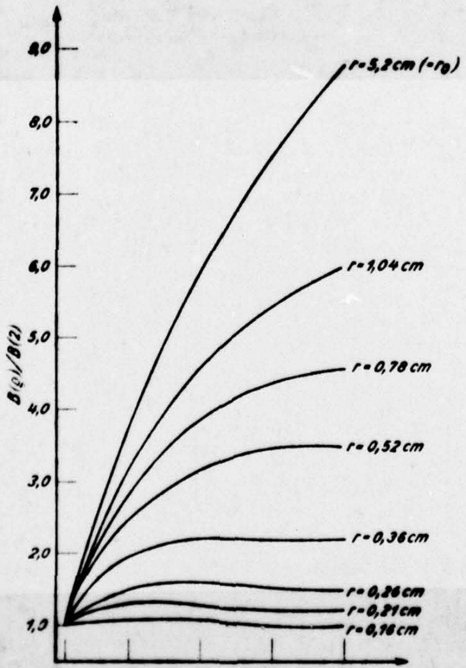


Fig. 7. Combination of initial field and compression.



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