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Evaluating the Limits of Shock Wave Magnetic Flux Compression in Solids

Contents

Abstract

In this paper we present the results of an investigation of the interaction of ionizing shock waves in solids with strong magnetic fields in the Shock Wave Magnetic Flux Compression (SWMFC) generator. Deceleration of the ionizing shock waves by magnetic pressure is calculated for cesium iodide (CsI). It will be shown that it is possible to evaluate the limiting magnetic pressure for the SWMFC by a relatively simple and clearly understandable method.

1. Introduction

The Shock Wave Magnetic Flux Compression (SWMFC) has been under development by Bichenkov [1] and Nagayama [2] since 1980. This method for magnetic flux compression uses a closed system of converging shocks that act upon a solid dielectric (called the working body), transforming it into a conducting state. If an initial magnetic flux is introduced into the working body, it is partially pushed into the non-conducting region ahead of the converging shock front and is compressed, while the remaining portion of the magnetic flux is lost from the compression region by "convection" and diffusion mechanisms. Ultra-strong fields (up to 350 T) were obtained by using this method in specially selected porous working bodies (aluminum and silicon powders) being compressed in transverse cylindrical shocks generated by chemical explosion or electro-explosion (see Fig. 1). Theoretical calculations [3–4] and experimental results [5] indicate that there is a difference in the dynamics of the initial and of the final stages of the flux compression process.

Prishchepenko [5] has shown that there is an abrupt change in the magnetic dipole moment, when the working body of the SWMFC is a single crystal of Cesium Iodide (CsI). This effect was explained to be due to oscillations of the shock wave velocity under the influence of strong magnetic field pressure during the final stage of compression. Unfortunately, a definite value for the magnetic field strength achieved in Prishchepenko's experiments has not been published [6]. Prishchepenko has also used single crystal of LiNbO3, which is known to be strong piezoelectric material capable of generating high voltages [7], in his experiments. When depolarized, it can produce electrical breakdown and associated RF emissions.

Bichenkov and his colleagues [8] have done a series of numerical calculations for porous materials and concluded that, for certain experimental device parameters, in addition to the limiting cases of shock wave deceleration by a strong field and of unlimited shock propagation, there is an *oscillatory* compression mode, where the pressure, the material density, and the local magnetic flux density oscillate *behind* the shock front. What magnetohydrodynamic (MHD) phenomena occur *ahead* of the shock front has not been studied by these authors, probably because of limitations in their experimental devices; that is, they could not make near-axis measurements due to the large size of the inductive magnetic field sensors. These authors have also shown that for the case of unlimited magnetic energy growth (which corresponds to a compression ratio in the working body greater than 2, which is realizable), the shock wave is decelerated by magnetic pressure until it is stopped. They obtained a formula for the magnetic field limit for the planar wave SWMFC and an ordinary differential equation for estimating the field limit for a converging cylindrical shock wave SWMFC. However, these results have slight relevance to the study of the physics of SWMFC, because they depend on such parameters as the liner mass in the shock wave source, which is only essential from an engineering point of view. If it is possible to derive a general expression for the dependence of shock propagation dynamics on shock pressure and magnetic pressure and for the working body equation-of-state (EOS), then a useful method could be developed for studying and evaluating the SWMFC.

2. Problem under Consideration

In this paper, we propose to seek the conditions that cause shock wave deceleration in strong fields. In plasma physics, a model for the "magnetic wall" concept, where shocks in plasmas are partially reflected from a magnetic field discontinuity, is known. Diffusion of the field through the shock front can be neglected, because of its high magnetic Reynolds' number, which is typical in SWMFC experiments. So the main parameter that affects the electromagnetic phenomena occurring within the generator is the magnetic field strength. In this case, we can assume that the interaction of the magnetic field with the ionizing shock occurs at the shock front. The flux density and the shock parameters can be evaluated independent of each other for each shock front position [9,10], so that it is now possible to study flux compression and the shock propagation processes separately. Then we will use a stepwise approximation for the magnetic field change in the compression zone instead of that of a monotonously increasing field. After each interaction of the *incident* ionizing shock wave with field discontinuities, *reflected* and *transmitted* waves are formed. The reflected wave travels backward and the transmitted wave, which is the remainder of the incident wave but with lower energy, travels forward. This model was suggested, calculated, and experimentally proven for gases by Bout and Gross [11] in 1970 for planar shocks. They evaluated the shock deceleration parameters by using the ideal gas approximation, assuming infinite conductivity and that the shock wave "forgets" about its source. So, it is suggested here to use this simple method, based on the approximation that the field jumps sharply from approximately zero to a finite final value (the x, t-diagram of this process is presented in Fig. 2). The transmitted wave, which weakens and which cannot switch on the conductivity of the compressed substance, will be gas dynamic, i.e., will not react with strong fields at all, and the strong reflected wave will propagate into the area where the field is too low to influence its propagation, so it can be considered to be gas dynamic as well. This simplification is allowable, because strong reflected waves can only occur during the final stage of operation of the SWMFC, which is the stage we want to focus on.

The field strength that yields a magnetic pressure capable of almost stopping the incident shock wave, calculated by using the approximations noted above, will be a maximum limiting value, since in Bout's paper it was shown that for a multi-step increase in the magnetic field, the shock wave deceleration will be even greater than that for the same final field strength.

3. Solution of the Problem

To solve this problem with this method, we will calculate the magnetic pressure at the moment the shock wave decelerates to the velocity of a weak non-ionizing shock wave and the field no longer interacts

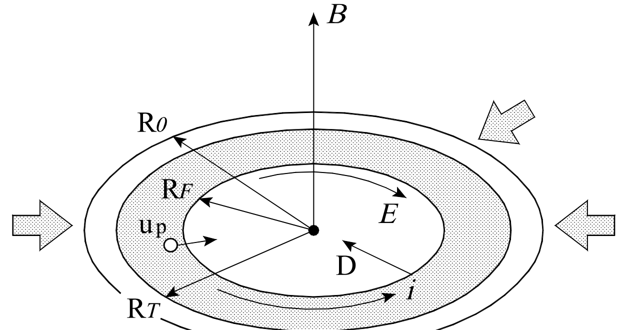

Fig. 1. Artist concept of Shock Wave Magnetic Flux Compression scheme: R_0 – radius of the working body at which the shock wave is initiated, R_T – radius of the working body after compression by the shock wave, R_F – shock front position, D – shock velocity, u_p – particle velocity of the compressed matter, E – electric field ahead of the shock front, i – current in the shock compressed working body, and B – magnetic field being amplified in the non-conductive area of the working body.

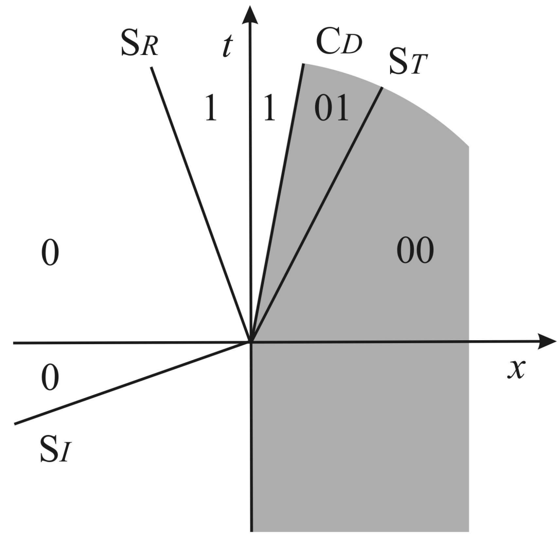

Fig. 2. x, t – Diagram of the shock with field interaction: S_I – incident shock wave, S_T – transmitted shock wave, S_R – reflected shock wave, C_D – contact discontinuity, 0 – compressed matter in the incident wave, 1 – compressed matter in the reflected wave, 01 – compressed matter in the transmitted wave, 00 – uncompressed matter, grey colored is matter inside the magnetic field.

with the working body under shock compression. When the reflected and transmitted waves propagate away from each other to a distance of at least a few orders of magnitude greater than the size of the atomic lattice elements (3.6 $\overset{0}{A}$), we notice the existence of a region, inside of which the incident shock has already interacted with the magnetic field, but geometrical changes of the shock intensity in both the reflected and transmitted waves remain negligible. The shock wave radius will be greater than the size of the above mentioned region by at least a few orders of magnitude, otherwise it will be problematic to consider the shock deceleration with this method. The influence of the cylindrical geometry on the propagation of reflected and transmitted shock waves outside of the selected region will not be considered, because already passed shocks commonly don't influence events that have already happened; that is, the incident wave interaction with the field discontinuity (this is called the "single reflection" approximation, since the influence of secondary interactions is assumed to be weaker). To analyze these processes, we can use the shock conditions at the discontinuity boundary, which are the same as those assumed for the *planar* shock wave case.

The EOS for a porous working body is not considered in our analysis, because of the sharp jump in the density from that of the initial packing of the porous material to that of a non-porous solid and because of the uncertainty in the pressure values for the same density when shock compressing high porous materials. So, we selected CsI, which was used in the experiments described in [6], as the working body. The minimum attainable pressure in the decelerated shock is that at which conductivity switches on; that is, where there is a sharp increase in conductivity. This is evident, because our model was developed from that with a multi-step increase of the magnetic field, where, if we consider the ionizing shock decaying to one of a non-ionizing amplitude, the further shock decay will not be possible, because the incident wave then does not switch on the conductivity and, thus, the compressed matter does not interact with the magnetic field discontinuity. It is also evident that the conductivity increase in solids occurs at a high compression ratio (for CsI the ratio ranges from 2 to 2.2), so one can't conclude that the material is *motionless* behind the transmitted shock. Therefore, we will consider the incident wave, the reflected wave and the transmitted wave. The latter should have pressure in the range where conductivity reversal occurs. The reflected wave pressure must be equal to the sum of the transmitted wave pressure and the magnetic pressure (otherwise additional shocks will occur) and the particle velocities must be equal (otherwise additional shocks or working body break up will occur). Thus, we have two gas dynamic shocks and one contact discontinuity between them. This situation is described by the shock conditions (the parameters are identical to those in Fig. 2) for the *reflected* shock:

$$E_1 - E_0 = \frac{(p_0 + p_1)}{2}(\eta_0 - \eta_1), \quad (1)$$

$$u_1 - u_0 = \sqrt{(p_1 - p_0)(\eta_0 - \eta_1)}, \quad (2)$$

where E is the specific energy, $\eta = 1/\rho$ is the specific volume, p is pressure, and u is particle velocity, and for the *transmitted* shock the boundary conditions are fulfilled:

$$\begin{aligned} E_{01} - E_{00} &= \frac{(p_{01} + p_{00})}{2}(\eta_{00} - \eta_{01}), \\ u_{01} &= \sqrt{(p_{01} - p_{00})(\eta_{00} - \eta_{01})}. \end{aligned} \quad (3)$$

We also have the conditions for contact discontinuity (which occurs at the moment of interaction of the incident shock with the field discontinuity):

$$p_1 = p_{01} + p_m, \quad u_{01} = u_1. \quad (4)$$

The simplest Mie-Gruneisen EOS in thermodynamic form $E(p, \eta)$ is taken from [12]:

$$E = \frac{p\eta}{\Gamma} - \frac{B(n-1-\Gamma)}{\Gamma(n-1)\eta^{n-1}}, \quad (5)$$

where the constants B,n, and (Gruneisen parameter) are calculated by using the experimental values for the shock adiabatic, and cold compression. The parameters of the working body *ahead of the transmitted* shock and *ahead of the reflected* shock (or similarly, *after the incident shock*) are fixed by the available experimental data [13–16].

Substituting Eq. 5 into Eq. 1, we obtain the shock adiabatic equation:

$$\frac{p_1\eta_1}{\Gamma_1} - \frac{B_1(n-1-\Gamma_1)}{\Gamma_1(n-1)\eta_1^{n-1}} - \frac{p_0\eta_0}{\Gamma_0} + \frac{B(n-1-\Gamma_0)}{\Gamma_0(n-1)\eta_0^{n-1}} = \frac{(p_0+p_1)}{2}(\eta_0 - \eta_1). \quad (6)$$

Substituting Eqs. 2–4 into Eq. 6, we obtain the following equation for p_m:

$$\frac{(p_{01}+p_m)\left(\eta_0 - \dfrac{(u_0-u_{01})^2}{p_{01}+p_m-p_0}\right)}{\Gamma_1} - \frac{B_1(n-1-\Gamma_1)}{\Gamma_1(n-1)\left(\eta_0 - \dfrac{(u_0-u_{01})^2}{p_{01}+p_m-p_0}\right)^{n-1}} - \frac{p_0\eta_0}{\Gamma_0} + \frac{B(n-1-\Gamma_0)}{\Gamma_0(n-1)\eta_0^{n-1}} = \frac{(p_{01}+p_m+p_0)}{2}\left(\frac{(u_0-u_{01})^2}{p_{01}+p_m-p_0}\right). \quad (7)$$

It is difficult to solve Eq. 7 analytically for all possible values of n. The numerical results for CsI are presented in Fig. 3. From (4), we see that the matter in the transmitted wave is only decelerated, but not actually stopped. Then the flux compression will partially continue by the means of the conductive matter in the reflected wave, while the matter in the transmitted shock will no more interact with magnetic field discontinuity. We still consider the problem as we have already done, because the further magnetic field growth occurs by the law of an ordinary magnetic flux compression, while we study the SWMFC only here. The SWMFC may continue after the transmitted shock becomes non-ionizing in some cases we will mention below.

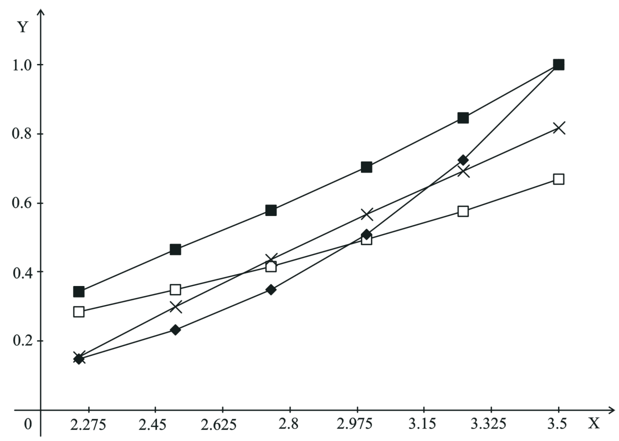

Fig. 3. Parameters of the shock wave-magnetic field interaction; that is, the relative compression of the incident wave (y-axis) vs. the compression ratio of the incident shock wave (x-axis): $D_R/D_{R_{\max}}$ – relative velocity of reflected wave (■); $D_0/D_{R_{\max}}$ – relative velocity of incident wave (□); $p_m/10p_{0_{\max}}$ – relative magnetic pressure (×); and $p_0/p_{0_{\max}}$ – relative shock pressure in the incident wave (⧫) when $D_{R_{\max}}$ = 21080 m/sec, p_0 = 645.2 GPa. $B \approx 3.2 \cdot 10^{-11}$ Pa, $n \approx 5.5$ all $\Gamma = 1.0$, except $\Gamma_{00} = 2.0$. The cold compression data for the high compression ratios was extrapolated from [16] based on Lennard-Jones theory. The shock induced conductivity threshold was chosen for the case where the compression ratio was 2.2.

The magnetic field does not affect the motion of the non-conducting portion of material, so after the *incident* shock decelerates, the *transmitted* shock with relatively strong pressure still propagates into the working body; moreover, in cylindrical geometries it converges and thus its intensity is amplified. That may continue up to the time the conductivity switches on and a secondary conducting region appears. It is evident that the secondary conducting zone will increase the dissipative losses due to the formation of an unstable shock, which decelerates rapidly from the time of occurrence, so that the resistivity will be higher than in the main conducting region. Thus one can predict that, inside the flux compression area, periodic wave structures can form, but we cannot evaluate their parameters by the method chosen due to the uncertainty in the conductivity reversal threshold in real shocks.

4. Discussion of the Results

Our data shows that for an incident shock pressure of 645 GPa (compression ratio is 3.5), the magnetic pressure required for shock wave deceleration down to the conductivity switch-on threshold is 5260 GPa (which corresponds to a field strength of 35 MG). This result is similar to that of Barmin (for a compression ratio of 3.33, the field strength was numerically calculated by using the full set of MHD partial differential equations (PDE's) and was found to be 55 MG [5]). The experimental results of Bichenkov show that for incident pressures of 5 GPa order, the magnetic pressure was 50 GPa (which corresponds to a field strength of 3.5 MG [9]).

Also, Bichenkov in [8] numerically predicted the existence of *matter density oscillations* behind the main shock wave front. In the case of high shock amplitudes, oscillations can split the main shock wave into separate shocks arranged in the form of spatially periodic wave structures (enclosed "recursively"), as predicted in this paper. It is evident, that one can also use other Bout's method, where the field is stepwise increased multiple times [11]. The reflected shock then must be considered to be magnetohydrodynamic. To simplify the solution, one can try linear or parabolic approximations for the dependency of the shock parameters on the compression ratio.

5. Conclusion

The magnetic field strength, required for the deceleration of the ionizing shock in solids, can be derived by solving the shock adiabatic equation for the known incident shock data and the equation-of-state with the conditions for the non-ionizing shock and contact discontinuity. Typically magnetic field pressure is a few times greater than the pressure of the incident wave [11]. For Cesium Iodide, the magnetic-to-hydrodynamic pressure ratio can be as high as 8 times. The higher the incident wave pressure, the higher the magnetic-to-hydrodynamic pressure ratio has to be to fulfill the condition for maximum possible ionizing shock deceleration.

6. Summary

In summary, it has been shown that it is possible to calculate the parameters of the SWMFC by a relatively simple and clearly understandable method. For Cesium Iodide, it was shown, that to fulfill the condition for maximum possible ionizing shock deceleration, the magnetic-to-hydrodynamic pressure ratio has to be as high as 8 times, and that the higher the incident wave pressure is, the higher the magnetic-to-hydrodynamic pressures ratio has to be.

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