Cylindrical isentropic compression by ultrahigh magnetic field

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Abstract. The cylindrical isentropic compression by ultrahigh magnetic field (MC-1) is a kind of unique high energy density technique. It has characters like ultrahigh pressure and low temperature rising, and would have widely used in areas like high pressure physics, new material synthesis and ultrahigh magnetic field physics. The Institute of Fluid Physics, Chinese Academy of Engineering Physics (IFP, CAEP) has begun the experiment since 2011 and a primary experimental device had been set-up. In the experiments, a seed magnetic field of 5 Tesla were set-up first and compressed by a stainless steel liner which is driven by high explosive initiated synchronously. The internal diameter of the liner is 97 mm, and its thickness is 1.5 mm. The movement of liner was recorded optically and a typical turnaround phenomenon was observed. From the photography results the liner was compressed smoothly and evenly and its average velocity was about 5-6 km/s. In the experiment a axial magnetic field of over 1400 Tesla has been recorded. The MC-1 process was numerical simulated by 1D MHD code MC11D and the simulations are in accord with the experiments.

1. Introduction
The method of magnetic flux compression by cylindrical explosive implosion is a unique technique of ultrahigh magnetic field generation [1-5]. The principle of this method is that of the conservation of magnetic flux enclosed within the boundary of a perfect conductor. Although the idea had been proposed more than half a century, it is still advantaged comparing with other dynamic techniques. Besides, the magnetic pressure during the ultrahigh magnetic field generation is a good tool of dynamic isentropic compression of samples. This technique has been used in many areas like high pressure physics, new material synthesizing and ultrahigh magnetic field physics [6-8].

2. Experiments
2.1. Experiment set-up
A schematic for the experimental set-up is presented in figure 1, which includes capacitor banks, switches, a pair of coils, a seamless liner, an explosive ring and a synchronous detonator. The initial fields are generated and diffused into the liner by discharging the capacitor banks through the coils at the two sides of the liner. The capacitor banks are triggered and discharged through the coils and the discharging current reaches its maximum in the end. The inner-field maximum occurs about 80-100 μs later, and the cylindrical ring of explosives drives the liner to implode simultaneously. The subsequent implosion of the liner compresses the magnetic flux with a corresponding increase in the magnetic field.
The capacitor banks consist of four 830-µF, 11-kV capacitors in all and are triggered by a semiconductor switch system. A pair of coils is arranged at the two sides of the liner. Each coil is organized by 16 turns of solid copper wire which are surrounded and reinforced by insulating materials. The liner is made of stainless steel and its internal diameter is 97 mm, 1.5 mm in thickness. The explosive used in the experiment is RDX/TNT (60/40) and 55 mm in thickness.

2.2. Numerical Simulations
The initial magnetic field distribution in our MC-1 set-up was simulated in figure 2 which shows a 5 Tesla of initial magnetic field could be obtained in the center of the liner by our facilities. The discharging current is about 40-50 kA, and the rising time is about 400-500 µs.

3. Experiment results
Till now we have performed several shots of experiments and the movement of liner were recorded. The frame images of liner movement in figure 3 were recorded by high-speed photography and we could see the liner compression and its turnaround process.
From the figure 4 we could obtain the displacement and velocity information of the liner. The average velocity of the liner is about 5-6 km/s.

We have carried out a 1-D hydrodynamic simulation of our experiments. The calculated result of liner movement and experiment result are shown in figure 5. According to the results, the experiment and the simulation are in good agreement with each other. The magnetic field history has also been simulated.

A typical magnetic field distribution in experiment is shown in figure 6 and a maximum field of about 1400 Tesla was obtained. The field measurements during the implosion were carried out by pickup coils. The probe includes 4 pickup coils of 5 mm interval each, so we could measure the histories of magnetic field at different positions on the central axis.
A copper tube compression experiment was carried out. In the experiment, a 16mm diameter of copper tube was compressed by MC-1 set-up. The PDV technique was used to measure the inner free surface velocity of the tube. The magnetic compression process was recorded by camera and shown in figure 7. The outer buckling of liner was serious because of elastic-plastic instability. In figure 8, the copper tube inner free surface velocity was obtained. It is quite clear that the MC-1 technique could be used as a kind of isentropic compression.

**Figure 6.** The magnetic field distribution in experiment.

**Figure 7.** A copper tube was compressed by MC-1. **Figure 8.** The copper tube inner surface velocity.

### 4. Analysis and conclusions

Before MC-1 technique was used as an effective isentropic compression method we have done some numerical simulations. In the simulations, the parameters of MC-1 set-up are the same with experiment, the sample is solid deuterium, and its density is 0.1766g/cm³. Two kinds of situation are considered, one is the compression by magnetic fields, and the other is the shock compression by explosive directly.
The simulated pressure histories on the surface of sample are shown in figure 9. Obviously, the magnetic compression is a kind of ramp wave loading and could be used as isentropic compression. The primary calculations show that the temperature in the magnetic-compressed sample is about 10-20 times lower than that in the shock situation.

Anyway, the MC-1 technique is verified by experiment and simulation as an effective isentropic compression method, and also as an ultrahigh magnetic field generation method. This technique could be used widely in high pressure physics, new material synthesis and ultrahigh magnetic field physics.

References
[1] Herlach F and Knoepfel H 1965 Rev. Sci. Instrum. 36 1088
[2] Fowler C M, Garn W B and Caird R S 1960 J. Appl. Phys. 31 588
[3] Hawke R. S, Duerre D E, Huebel J G, Klapper H, Steinberg D J and Keeler R N 1972 J. Appl. Phys. 43 2734
[4] Pavlovskii A I, Dolotenko M I and Kolokolchikov N P 1984 Ultrahigh magnetic fields: Physics Techniques Eds. Titov V M and Shvetsov G A ( Moscow: Nauka) p19
[5] Boyko B A, Bykov A I, Dolotenko M I, Kolokolchikov N P, Markevtsev I M, Tatsenko O M and Shuvalov A M 1998 Proceeding of the VIIIfth international conference on megagauss magnetic field generation and related topics Edited by Hans J Schneider-Muntau p 61
[6] Clark R G 1998 Proceeding of the VIIIfth international conference on megagauss magnetic field generation and related topics Edited by Hans J Schneider-Muntau p 12
[7] Lindemuth I R 1997 IEEE Transactions on Plasma Science 25 534
[8] Boriskov G V, Belov S I, Bykov A I, Dolotenkon M I, Egorov I, Korshunov A S, Kudasov Y B, Makarov I V, Selemir V D and Filippov A V 2010 J. Low. Temp. Phys. 159 307