Space-Time-Controlled Multi-Stage Pulsed Magnetic Field Forming

Liang Li¹, Xiaotao Han¹, Li Qiu¹, Zhongyu Zhou¹, Tao Peng¹, Hongfa Ding¹, Jianjun Li², Lin Liu², Jianhua Mo², Liang Huang²

1. Wuhan National High Magnetic Field Center (WHMFC),
2. College of Materials Science and Engineering, Huazhong University of Science & Technology (HUST), Wuhan, 430074, P.R.China
Introduction of WHMFC

Concept of Space-Time-Controlled Multi-Stage Pulsed Magnetic Field (Stic-Must-PMF) Forming and Manufacturing Technology

Recent progress of Stic-Must-PMF at Pulsed Magnetic Field Forming

Conclusion
Where is WHMFC?
Wuhan City

- The capital of Hubei province,
- The most populous city in central China with a population of approximately 9,100,000 people.
- Big joint center of railways, waterways and the airlines
- 22 Colleges and universities
  - 8 national colleges and universities,
  - 14 public colleges and universities.
Huazhong University of Science and Technology

- One of leading universities of the Ministry of Education in China.
- 2 National laboratory
- 4 National Leading Laboratories,
- 5 National Engineering Research Centers,
- 27 Leading Laboratories of Ministerial and Provincial Level.
- 29 key subjects are national level and 28 key subjects are ministerial and provincial level.
- 11 full academicians and 5 part-time academicians of the CAS and CAE.

- Full-time students > 50,000
  - 14,000 MSs and 5,300 Ph.Ds.
- Faculty members >10,000,
  - 1016 full professors
  - 1,348 associate professors.
- Area covers: 4,689,323 square meters.
Taking the pulse of magnet labs

As fields get stronger and electronics improve, demand for pulsed magnets is growing; the newest lab is in China.

Quickly catching up with the more established pulsed-field labs is the Wuhan National High Magnetic Field Center in central China. It was founded in 2008 and is scheduled to open to users in 2013. The CNY180 million (roughly $28 million) Wuhan lab at Huazhong University of Science and Technology is the first major scientific facility in China to be under the auspices of a university rather than the Chinese Academy of Sciences. A sister lab in Hefei that focuses on static magnets is comparable to centers in Tallahassee; Tsukuba, Japan; Grenoble, France; and Nijmegen, the Netherlands.

Liang Li, the director of the Wuhan lab, earlier worked in Europe and the US and designed pulsed magnets at the NHMFL. So far, 7 of 11 planned experimental stations at Wuhan are ready; they are outfitted with low-temperature cryostats, lasers, and other instruments. Li says the Chinese lab has achieved 78.8 T and plans to test its first dual-stage magnet this month. “We will get as high as we can, hopefully to 85 T.”

Toni Feder
The Structure of the Pulsed Field Facility at WHMFC

- 10kV母线
- 14.8 MJ/25kV capacitor bank
- 100MVA/100MJ pulse generator
- 100MVA/100MJ pulse generator
- SP magnets
- LP magnets
- LSP magnets
- test magnets
- SC magnets
- Transport cell
- Magnetization cell
- magneto-optics cell
- High Pressure
- ESR
- PPMS & SQUID
- Other Applications
- LN2 77k
- 4He 1.5K - 4.2K
- 3He 300mK
- 3He-4He 50 mk
- laser
- 高压
- 公用及辅助设施
- 土建工程

- 氦液化器和超流氦系统
- 3He-4He 稀释制冷机
- (30mK)
- 3He 制冷机
- (300mK)
- 光源

- 磁光特性科学实验测试系统
- 电容器模块
  - 1 (1MJ)
  - 2 (1MJ)
  - 3 (1MJ)
  - 4 (1MJ)
  - 5 (1MJ)
  - 6 (1MJ)
  - 7 (1MJ)
  - 8 (1MJ)
  - 9 (1MJ)
  - 10 (1MJ)
  - 11 (1MJ)
  - 12 (0.5MJ)
  - 13 (0.5MJ)

- 实验筛选与标定室
- 超导磁体
- 压力效应科学实验测试系统
- 极低温科学实验测试系统
- 脉冲磁体测试室
- 待测磁体

- 调速系统
- 励磁系统

- 实验室
- 监控系统

- 公用及辅助设施监控系统

- 主监控系统
The Structure of the Pulsed Field Facility at WHMFC

3He制冷机 (300mK)

光源

磁光特性科学实验测试系统

电容器模块 6 (1MJ)
电容器模块 7 (1MJ)
电容器模块 5 (1MJ)
电容器模块 2 (1MJ)
电容器模块 8 (1MJ)
电容器模块 4 (1MJ)

氦液化器和超流氦系统

3He-4He稀释制冷机 (30mK)

高静压10kV母线

公用及辅助设施

科学实验测试系统

监控系统

电容器模块 9 (1MJ)
电容器模块 10 (1MJ)

实验筛选与标定室

超导磁体

压力效应科学实验测试系统

极低温科学实验测试系统

脉冲磁体测试室

待测磁体

调速系统

液氮储槽 (77K)

励磁系统

G M
SP magnets
LP magnets
LSP magnets
SC magnets
test magnets
Transport cell
Magnetization cell
magneto-optics cell
ESR
High Pressure
Other Applications
4He
1.5K - 4.2K
LN2
77k
3He
300mK
3He-4He
50 mk

14.8 MJ/25kV capacitor bank
100MVA/100MJ pulse generator
SP magnets
LP magnets
LSP magnets
SC magnets
test magnets
Transport cell
Magnetization cell
magneto-optics cell
ESR
High Pressure
Other Applications
4He
1.5K - 4.2K
LN2
77k
3He
300mK
3He-4He
50 mk
The Objectives

Parameters of pulsed Magnet and Field waveform

<table>
<thead>
<tr>
<th>Field (T)</th>
<th>Power type</th>
<th>Bore (mm)</th>
<th>Pulse duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short pulse</strong></td>
<td>50</td>
<td>C</td>
<td>34</td>
</tr>
<tr>
<td>60</td>
<td>C</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>70</td>
<td>C</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>C</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td><strong>Long pulse</strong></td>
<td>50</td>
<td>G^a</td>
<td>22</td>
</tr>
<tr>
<td>60</td>
<td>C</td>
<td>26</td>
<td>200</td>
</tr>
<tr>
<td><strong>Dual stage</strong></td>
<td>80</td>
<td>C</td>
<td>14</td>
</tr>
</tbody>
</table>
The Objectives

Parameters of pulsed Magnet and Field waveform

- Short pulse
- Long pulse
- Dual stage

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>PMT50S</th>
<th>PMT60S</th>
<th>PMT70S</th>
<th>PMT80S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Pulse duration (ms)
The Objectives

- Parameters of pulsed Magnet and Field waveform

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Magnet Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>Bin</td>
</tr>
<tr>
<td>30-50</td>
<td>Bout</td>
</tr>
<tr>
<td>60-80</td>
<td>Bsum</td>
</tr>
</tbody>
</table>

The Objectives
The Objectives

- Parameters of pulsed Magnet and Field waveform

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Magnetic field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>
Power Supplies

- Completed the construction of the 14.8MJ/25kV capacitor bank, of which two modules have been pulsed over 3000 shots with no problem.
Pulsed-generator has been installed and in operation for 3 years with no fault.

**ØGenerator:**
- Capacity: 100MVA
- Energy output: 100MJ
- Rotor speed: 495–713rpm
- Rated output voltage: 6.9kV

**ØMotor:**
- Capacity: 1417kW
- Rated input voltage: 10kV
- Rated speed: 713rpm
A pulsed magnet designing software has been developed which solves the coupled electromagnetic-mechanical-thermal model with a user friendly interface and has been widely used by other high magnetic field labs.
Magnets

A pulsed magnet designing software has been developed which solves the coupled electromagnetic-mechanical-thermal model with a user friendly interface and has been widely used by other high magnetic field labs.
Magnets

- Coil Winding machine has been in service since 2009.
Magnets

- Short pulse magnet made of soft copper successfully reached 78 T non-destructively.

- Completed 8 short-pulsed magnets intensity ranged from 50T to 78T.
Magnets

- Dual stage pulsed magnet reached 83 T non-destructively
Completed the hardware & software installation of the controlling system; The security & warning system and monitoring system are in service. The whole system is in operation now.
Developed 7 measurement stations

- Magneto-Optics
- Transport and Magnetization
- Extremely Low Temperature system
- ESR system
Applications of pulsed high magnetic field at WHMFC

- Pulsed High Magnetic Field Facility
- Electromagnetic Forming
- Magnetic refrigeration
- Eddy current breaking
- Post magnetization
Compact Pulsed High Magnetic Field Facility

- Automatic charge-discharge operation repeatedly under 50 T high field.
- Integrated pulsed magnet, pulsed power source and corresponding control system as well as its interface.
- Can be applied as a research device independently as well as integrated into other facility as an optional component.
- Compact size, Friendly interface and low cost.
Limitations of the conventional electromagnetic forming

- Single coil structure, the Lorenz force on the workpiece decreases rapidly.
- The magnetic field strength is normally low (<10T), the energy of the power supply is mostly less than 100kJ.

Requirements for large deformation parts forming

- Higher magnetic field strength
- Wider magnetic field region
- More flexible timing control

Development trend of the electromagnetic forming

- Applying to form small, thin-walled workpieces and local forming only
Foundation for Stic-Must-PMF

- WHMFC has owned key technologies for Stic-Must-PMF
  - Ultra-high field pulsed magnet
  - High density pulsed power source
  - Accurate magnetic field space-time control

- A magnetic field intensity of **83T** was achieved by using two-stage coil structure, multi-module power supply and timing control technology.
Concept of Stic-Must-PMF Forming Technology

Schematic illustration of the multiple space-time HPMF deep drawing forming system

Funded as the National Basic Research Program of China (973 Project) by the Chinese ministry of Science and Technology, total funding budget is 38 M Chinese Yuan (4 M Euro);
Potential Applications

- Coils miniaturization and arrays design
- Ultra-fast pulsed high power source
- Multiple coils
- Combination long-pulse coil with short-pulse coil
- Multiple power sources

large-scale sheet
Plastic flow forming

Stic-Must
-PMF

- Coils miniaturization and arrays design
- Ultra-fast pulsed high power source

large-scale panel
internal stress adjustment and control

abnormity tube
Local flow and interface connection

- High strength coil
- Continuous discharge coil
How to generate the Space-Time-Controlled Multi-Stage pulsed magnetic field?

Challenges to the Forming Equipment

- Multi-stage and multi-direction magnetic field distribution
- Electromagnetic coupling among multi coils
- Complex interrelation between the magnetic field and materials
- Difficulties for optimal design of coils strength and arrangement

- Magnetic force among multi coils
- Skin effect, magneto-resistance effect
Technological Difficulties

- Coupled analysis of electro-magnetic field, stress field and heat field
- Optimal design of magnetic field, coil structure and spatial arrangement
- Design of modular power system and timing control system

Difficulties

Coupled analysis of electro-magnetic field, stress field and heat field

Optimal design of magnetic field, coil structure and spatial arrangement

Design of modular power system and timing control system

Theoretical analysis

 structural design

 System integration
Research Contents

Research content

- The effective regulation of the magnetic field and electromagnetic force for the multi-stage and multi-direction PHMF system
- The magnetic field penetration, eddy current distribution and the energy conversion law involved in the forming of complex structures
- Modeling and design criteria for the multi-stage and multi-direction PHMF system
- Building the experimental platform of multi-stage and multi-direction HPMF system for large-scale and complex work pieces

Expected breakthrough

- Revealing the laws of magnetic field and electromagnetic force in multiple-coil system
- Breaking through technical bottleneck of Stic-Must-PMF forming and manufacturing system

Expected results

- Design theory and method of space-time-controlled multi-stage electromagnetic force

Equipment Characteristic

- Magnetic flux density: 0~50T
- Power energy: <1000 kJ
- Multi-stage control: >3
- Auxiliary heating, edge pressing and assembling integration
Technical Solution

Research Program

- Structure optimization design of electromagnetic coils
- Modular power design
- Timing logical control

Electromagnetic parts design

Major facility prototype

Theoretical analysis

Forming concept

- Experiment test platform
- Experimental Verification of process parameters
- Model calibration and modification

- Magnetic field distribution
- Forming force distribution
- Energy conversion
- Work-piece motion law

Forming concept

- Various components and configurations of electromagnetic parts
WHMFC has built a 2mF/8kV/20kA electromagnetic forming equipment, and researched the electromagnetic forming, hole flanging, and cutting using the equipment.
Recent progress at Pulsed Magnetic Field Forming


- Plastic flow is very important to deep drawing

Right figure shows that the aluminium sheet workpiece after free bulging exists plastic flow in the electromagnetic forming process, which the whole sheet flowed into the die.

Sheet thickness is 1 mm, sheet diameter is 140 mm, the die diameter is 100 mm.
Conclusion

- A new high field pulsed magnetic field facility is under development with 14.8 MJ/ 25 kV capacitor bank and 100 MJ/ 100 MVA pulse generator as its power supplies.
- Pulsed magnets made of soft copper has successfully reached 78 T, Dual stage pulsed magnet reached 83 T non-destructively;
- A new concept of Space-Time-Controlled Multi-Stage Pulsed Magnetic Field forming has been proposed;
- The Stic-Must-PMF forming project has been funded as the National Basic Research Program of China (973 Program, 2011CB012800) by the Chinese ministry of Science and Technology, total funding budget is 38 M Chinese Yuan (4 M Euro);
- The objective of the project is the development a prototype electromagnetic forming facility that can do sheet forming, surface work hardening, internal stress shape adjustment and composites tube forming.
谢谢！