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

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Outline

- 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 rail ways, water ways and the airlines
- 22 Colleges and universities
  8 national colleges and universities,
  14 public colleges and universities.

Huazhong University of Science and Technology

- 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

- 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.

Wuhan National High Magnetic Field Center

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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.

YUAN CHENG/WUHAN NATIONAL HIGH MAGNETIC FIELD CENTER

China's Wuhan National High Magnetic Field Center is the newest high-field pulsed magnet lab.

Quickly catching up with the more established pulsed-field labs is the Wuhan National High Magnetic Field Center in central China. It was founded

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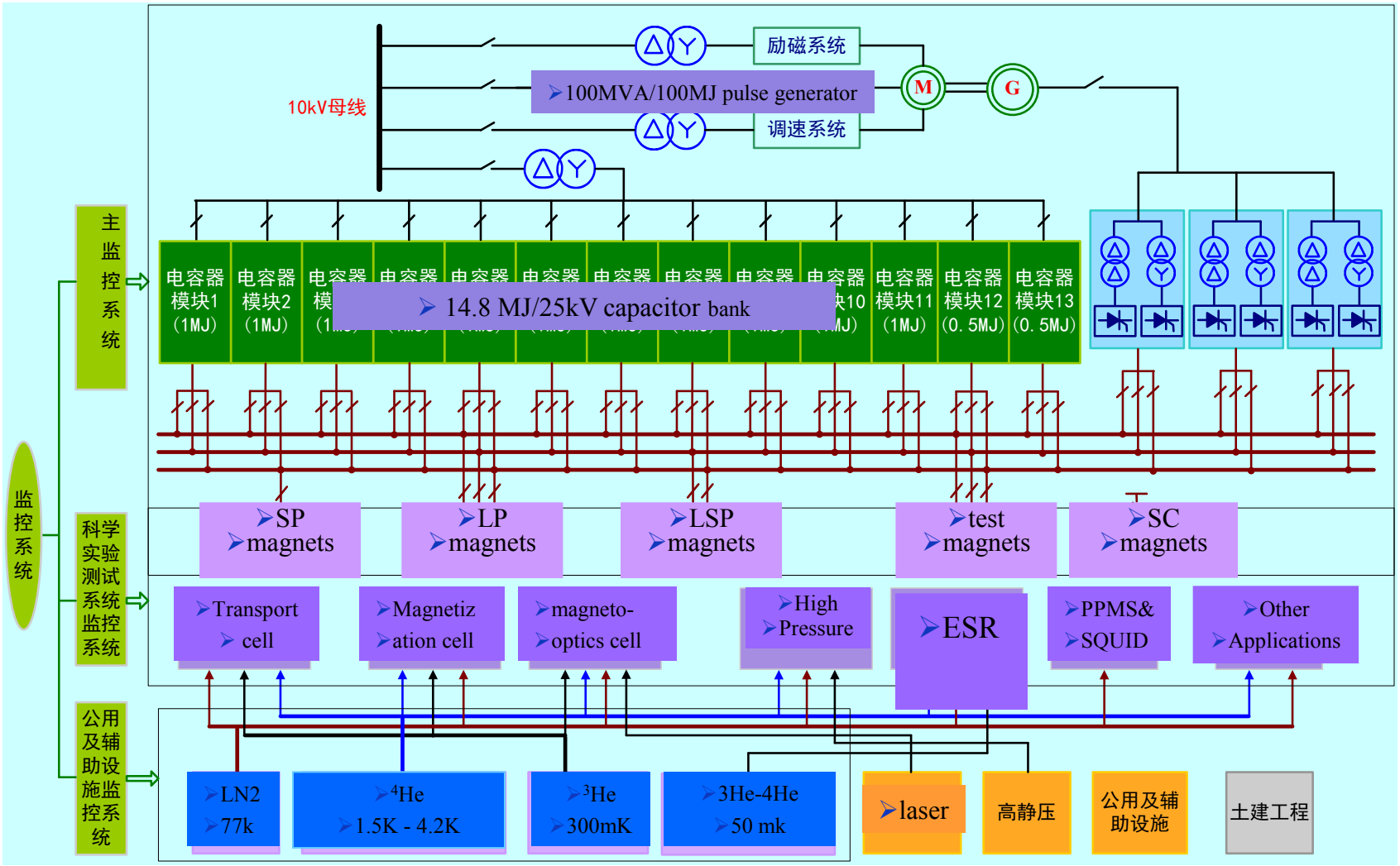
in 2008 and is scheduled to open to users in 2013. The CNY180 million (roughly $28 million) Wuhan lab at Huazhong University of Science and Technology is the first major scientific facility in China to be under the auspices of a university rather than the Chinese Academy of Sciences. A sister lab in Hefei that focuses on static magnets is comparable to centers in Tallahassee; Tsukuba, Japan; Grenoble, France; and Nijmegen, the Netherlands.

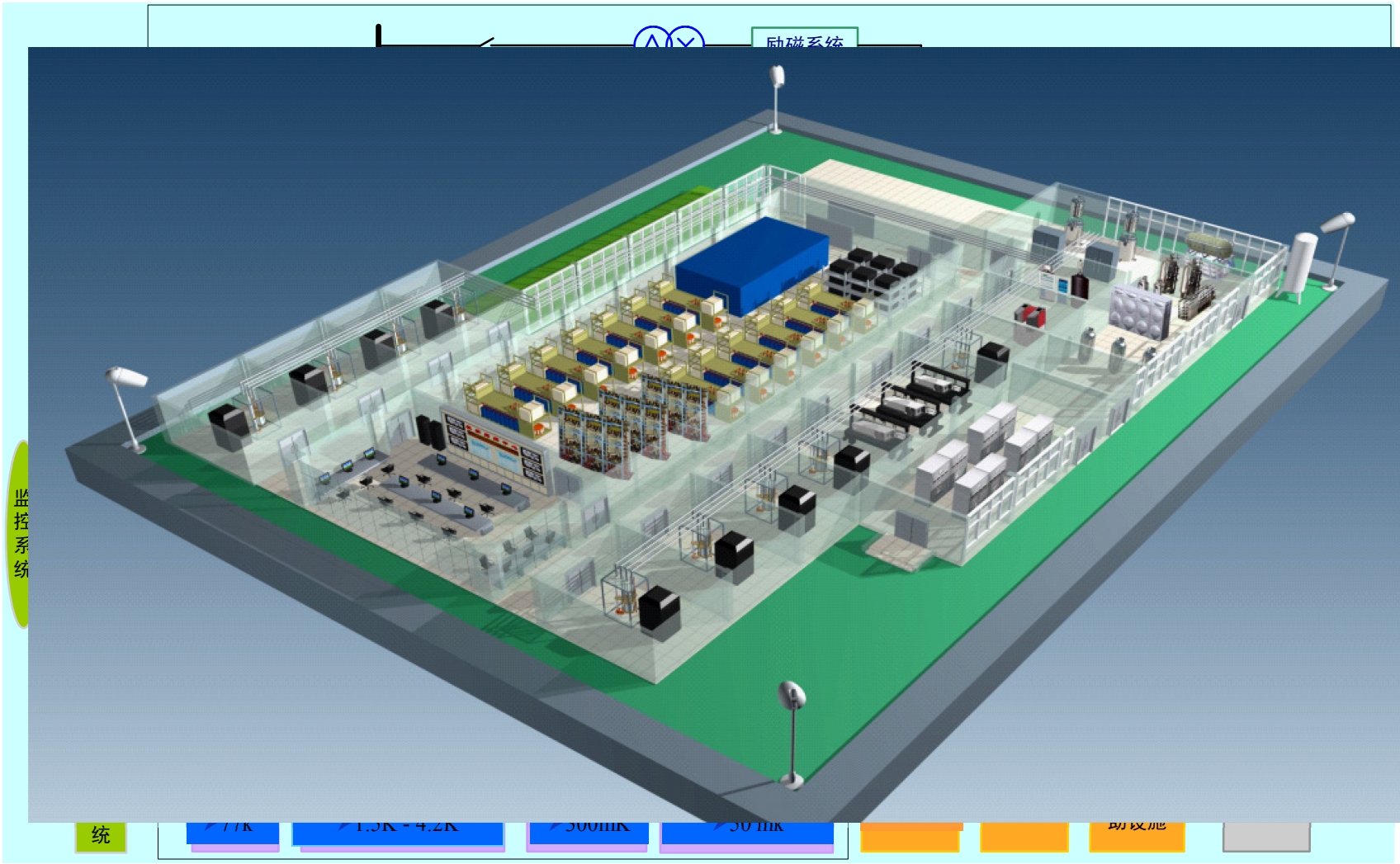
Liang Li, the director of the Wuhan lab, earlier worked in Europe and the US and designed pulsed magnets at the NHMFL. So far, 7 of 11 planned experimental stations at Wuhan are ready; they are outfitted with low-temperature cryostats, lasers, and other instruments. Li says the Chinese lab has achieved 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



The Structure of the Pulsed Field Facility at WHMFC



The Objectives

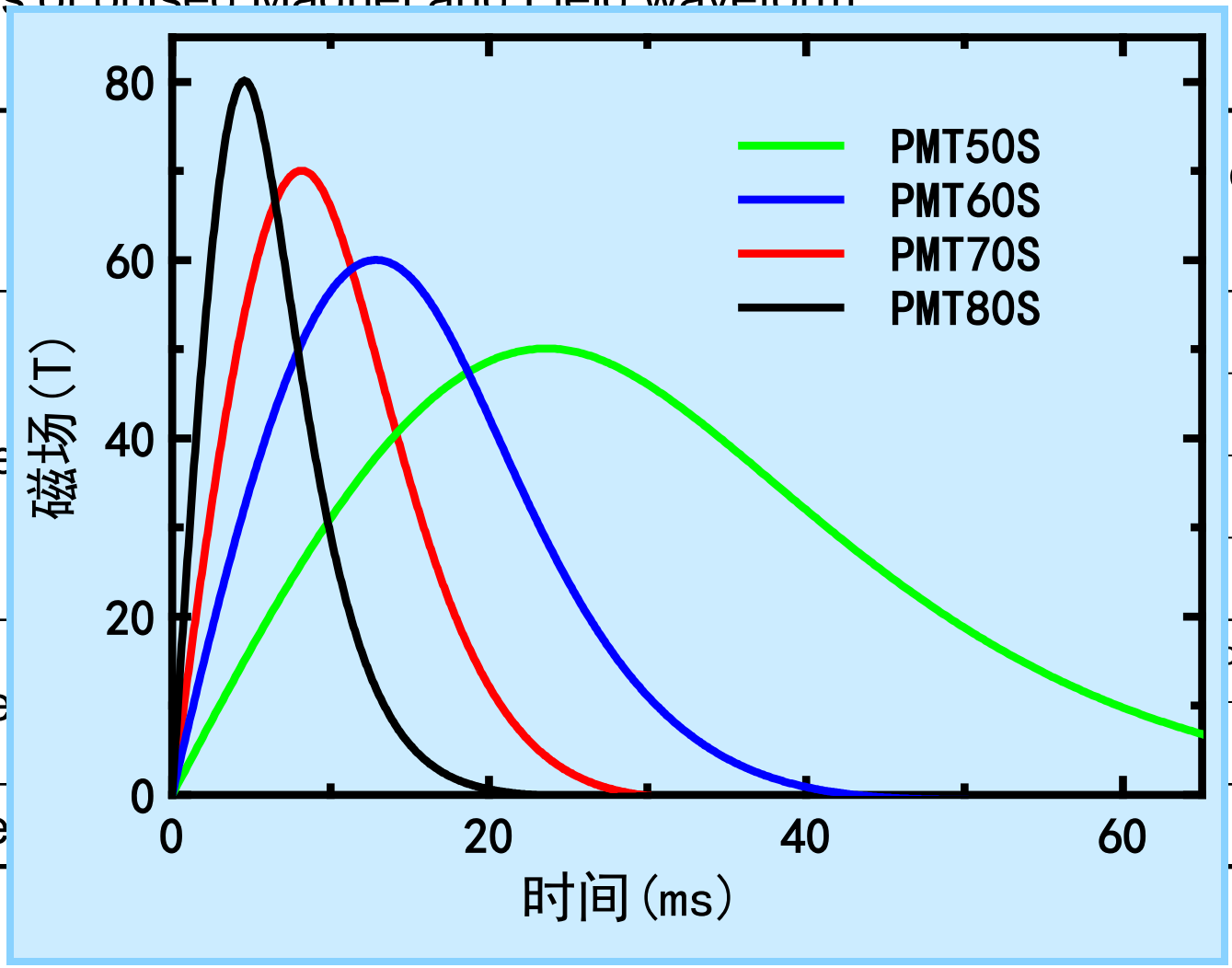
- Parameters of pulsed Magnet and Field waveform

	Field (T)	Power type	Bore (mm)	Pulse duration (ms)
Short pulse	50	C	34	65
	60	C	22	30
	70	C	14	20
	80	C	12	15
Long pulse	50	G[a]	22	2250/100[b]
	60	C	26	200
Dual stage	80	C	14	200/8[c]

The Objectives

- Parameters of pulsed Magnet and Field waveform

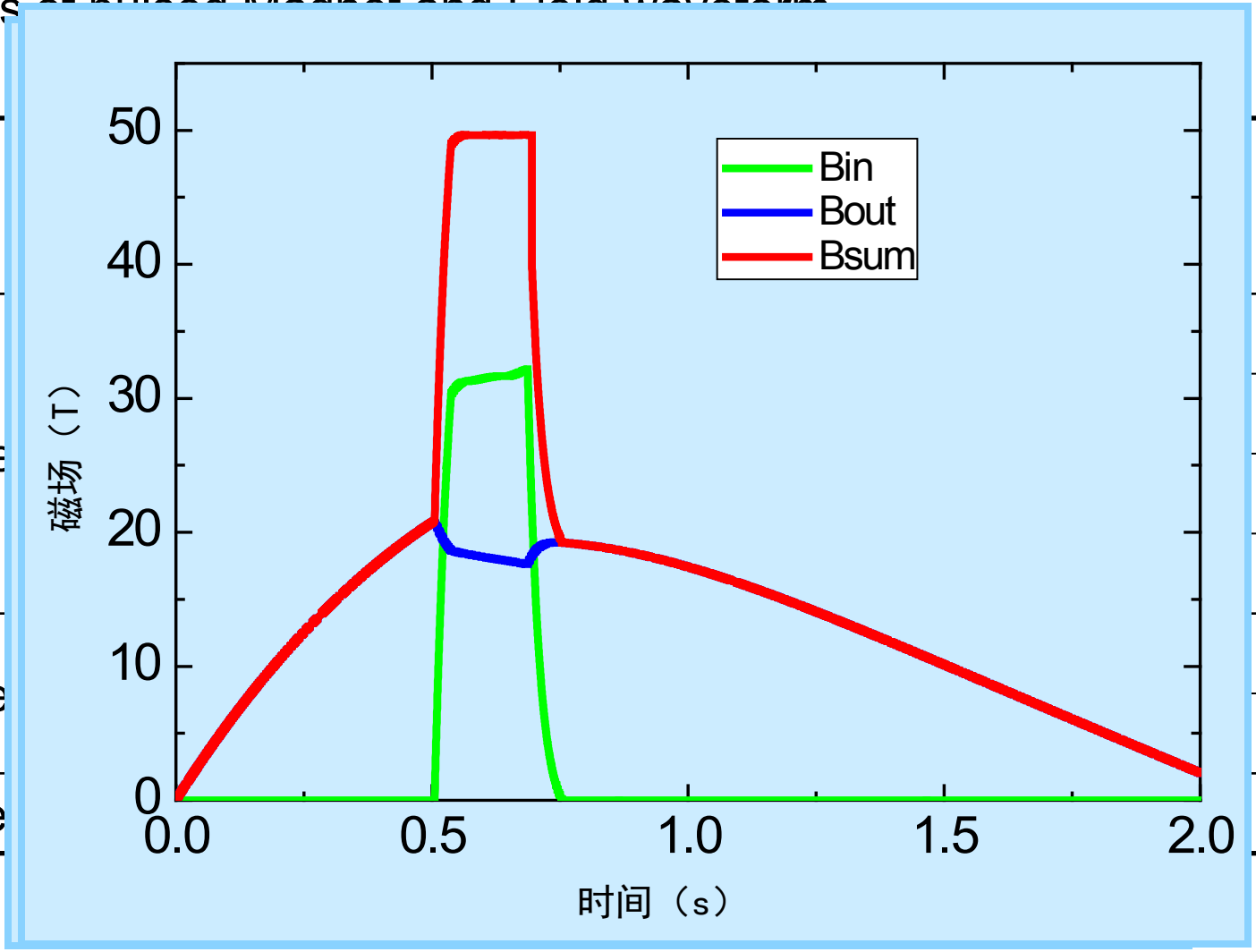
Short pulse	
Long pulse	
Dual stage	



The Objectives

- Parameters of pulsed Magnet and Field waveform

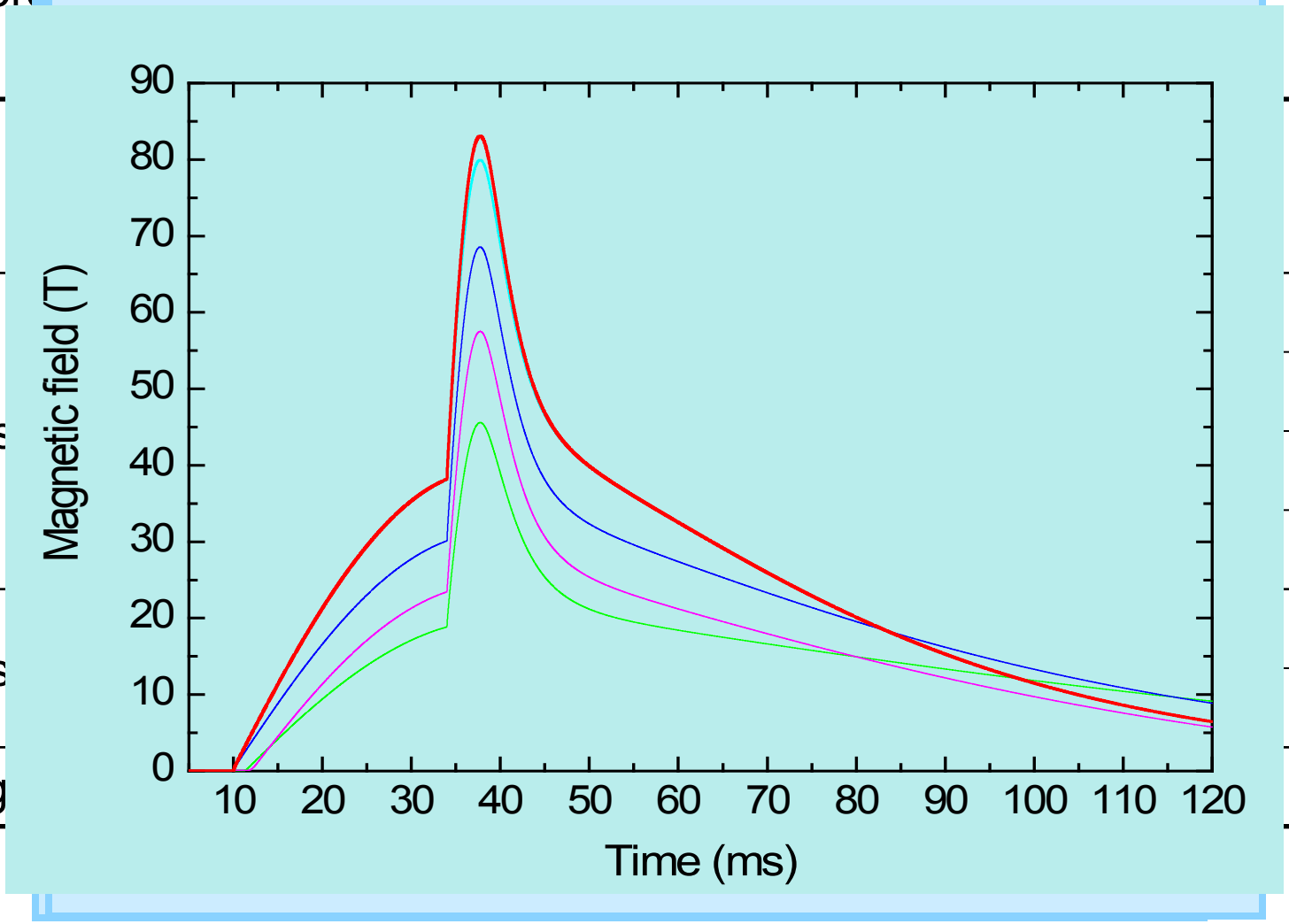
Short pulse	
Long pulse	
Dual stage	



The Objectives

- Parameters of pulsed Magnet and Field waveform

Short puls	
Long puls	
Dual stag	

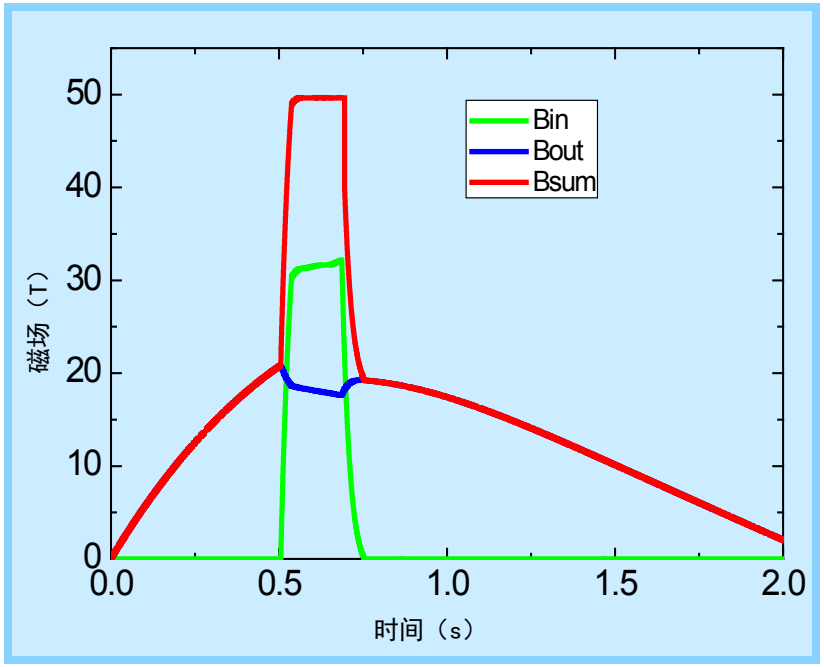


Power Supplies

- Completed the construction of the 14.8MJ/25kV capacitor bank, of which two modules have been pulsed over 3000 shots with no problem.

Power Supplies

Pulsed-generator has been installed and in operation for 3 years with no fault.



Ø**Generator：**

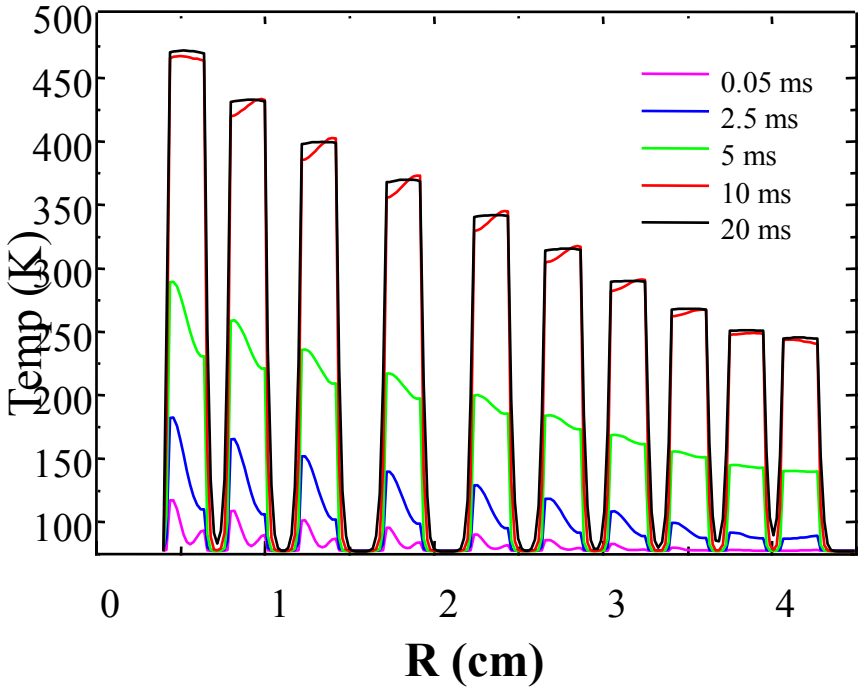
- Ø **Capacity：100MVA**
- Ø **Energy output：100MJ**
- Ø **Rotor speed：495—713rpm**
- Ø **Rated output voltage：6.9kV**

Ø**Motor：**

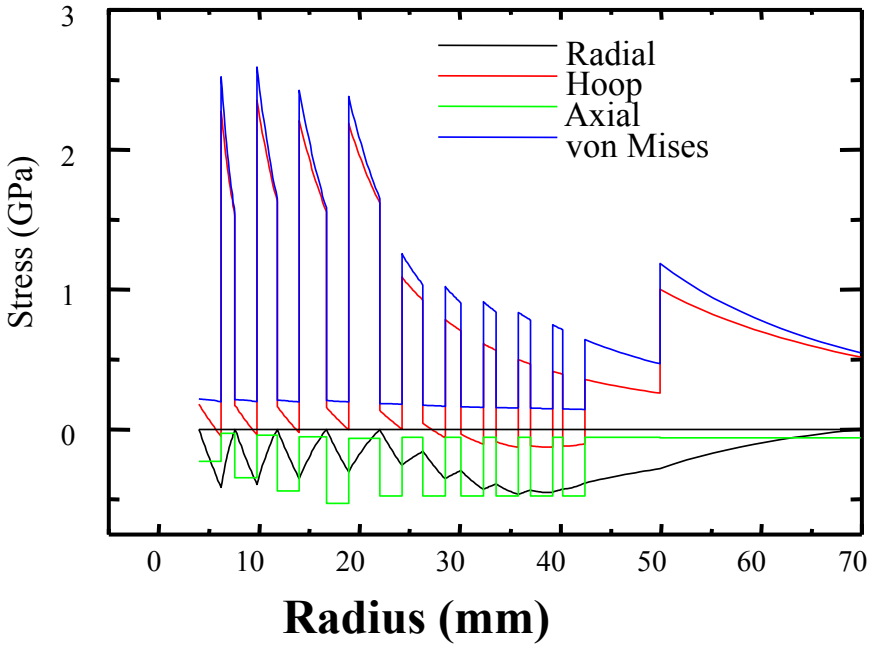
- Ø **Capacity：1417kW**
- Ø **Rated input voltage：10kV**
- Ø **Rated speed：713rpm**

Magnets

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



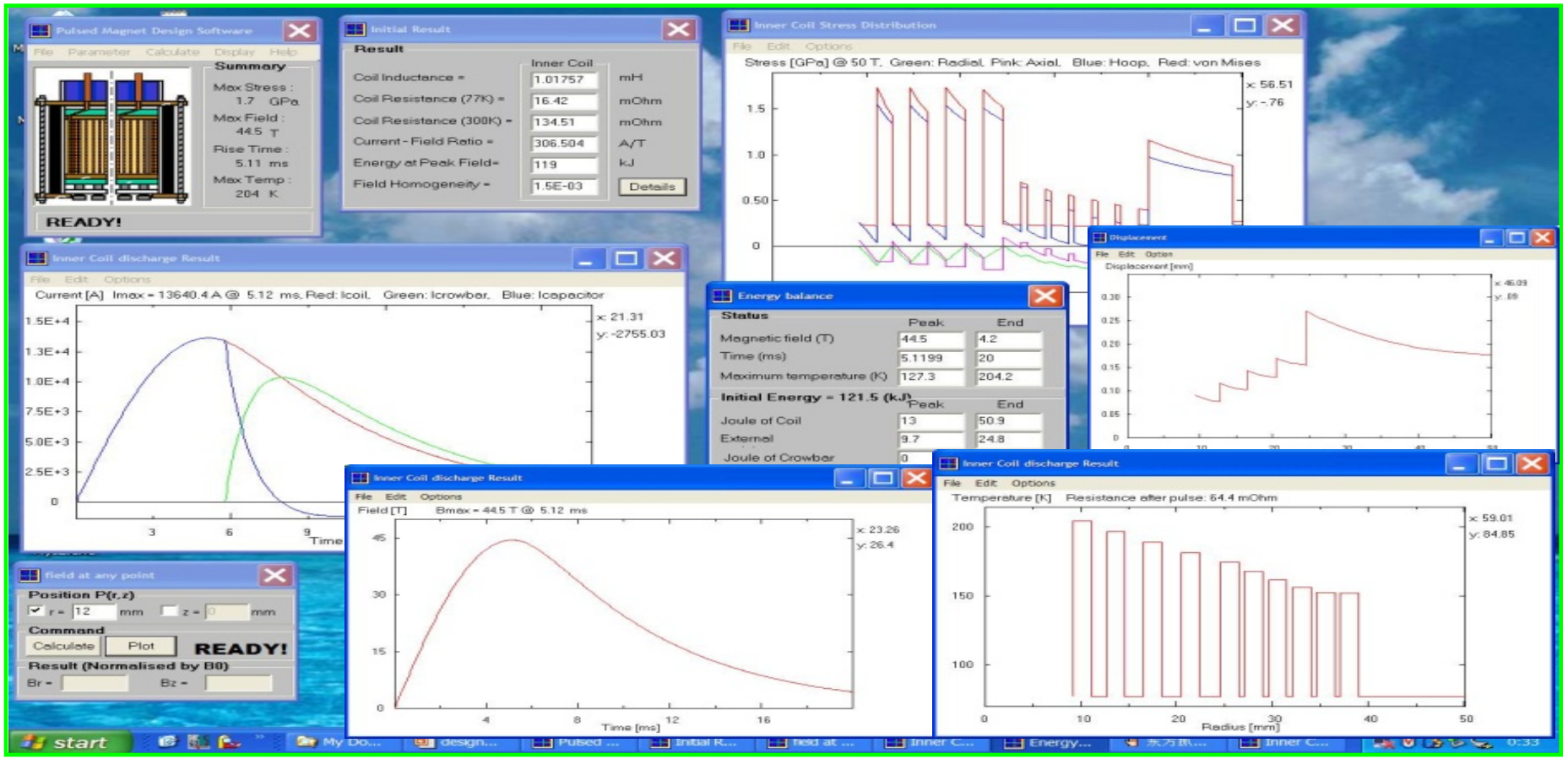
Thermal Distribution



Stress Distribution

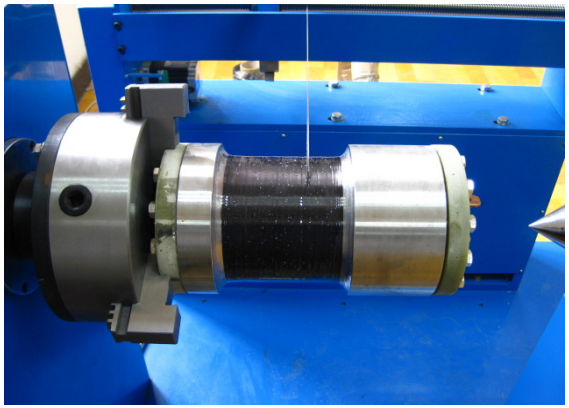
Magnets

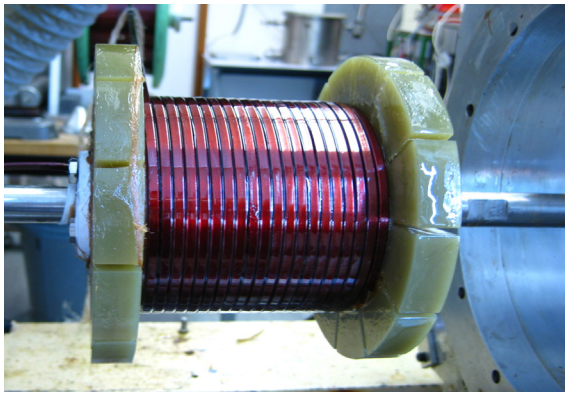
A pulsed magnet designing software has been developed which solves the coupled electromagnetic-mechancial-thermal model with a user friendly interfaceand has been widely used by other high magnetic field labs.

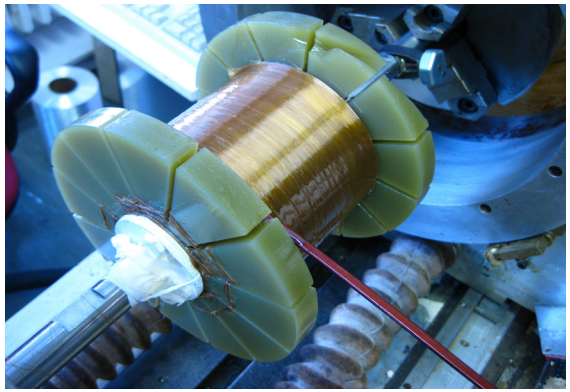


Magnets

- Coil Winding machine has been in service since 2009.

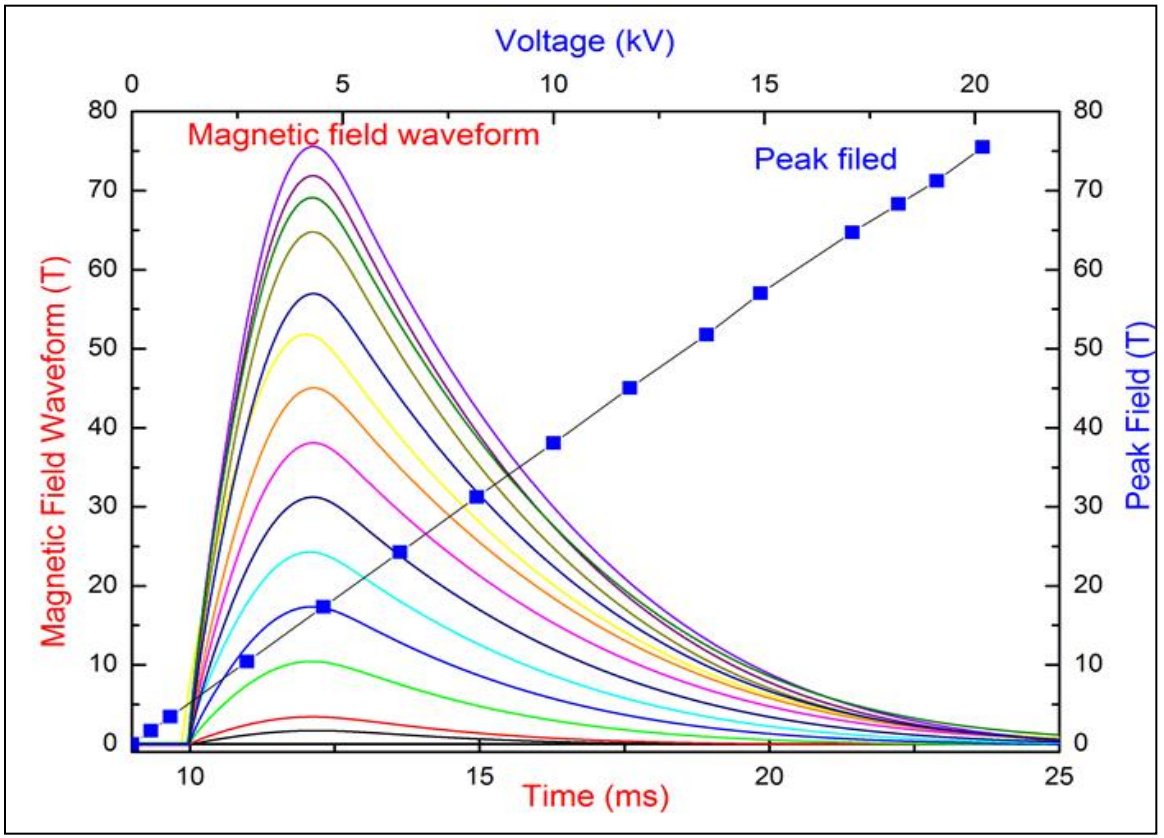






Magnets

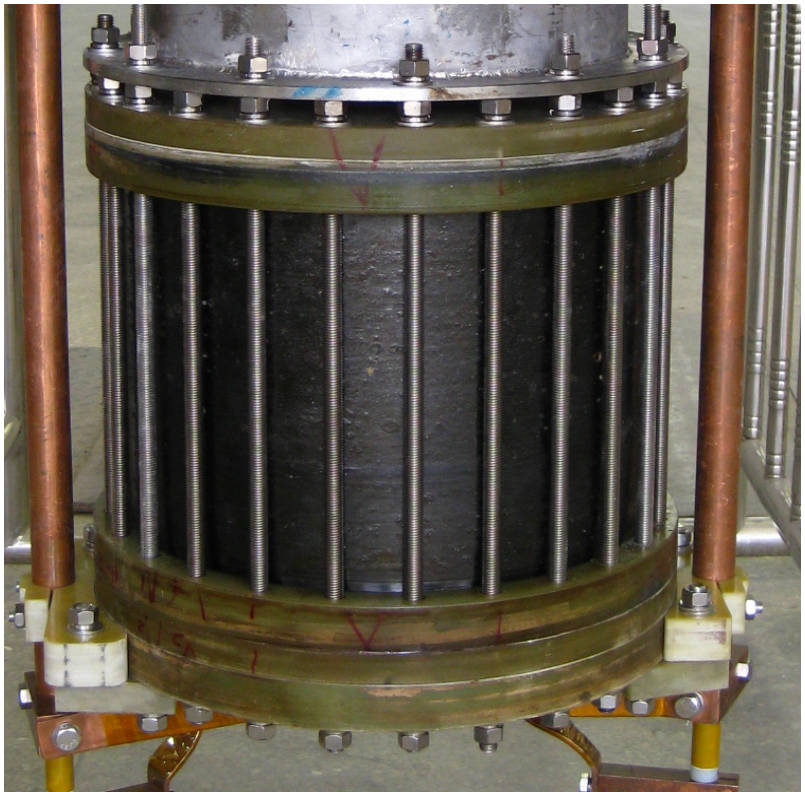
- Short pulse magnet made of soft copper successfully reached 78 T non-destructively

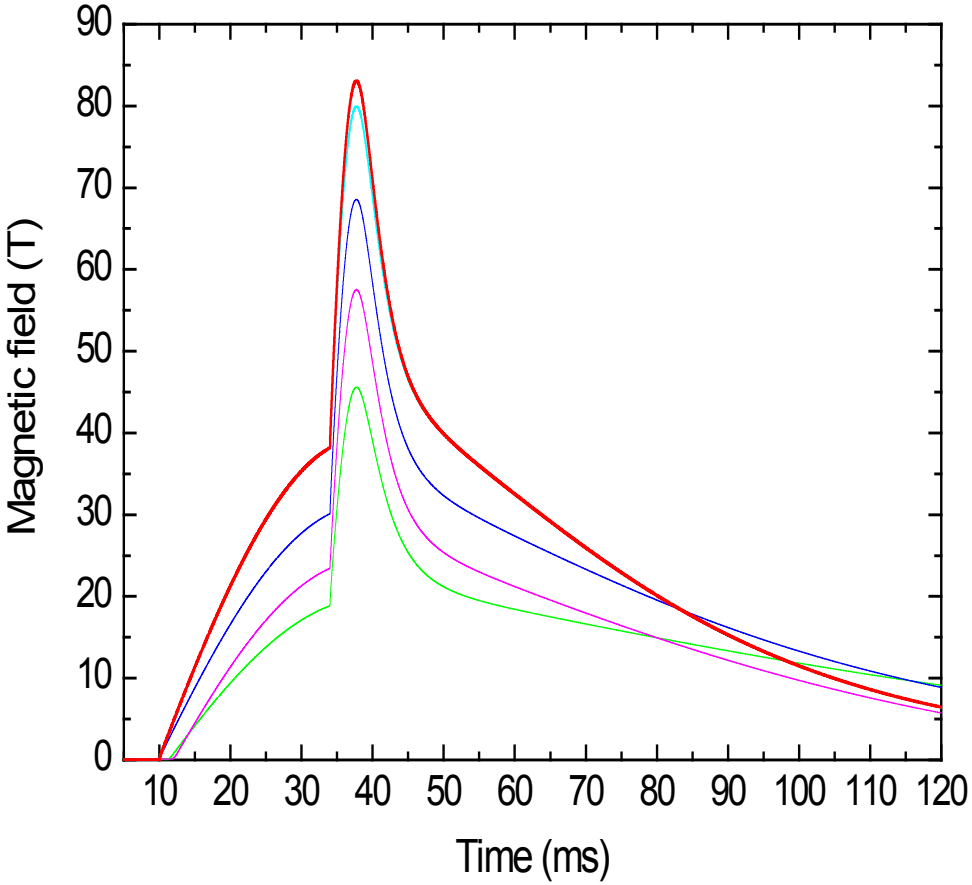


- Completed 8 short-pulsed magnets intensity ranged from 50T to 78T.

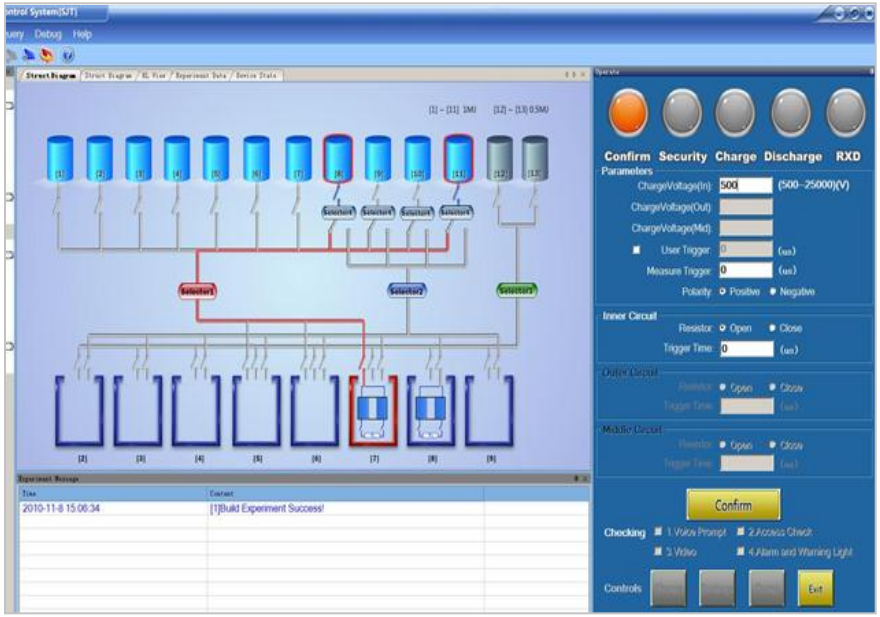
Magnets

- Dual stage pulsed magnet reached 83 T non-destructively





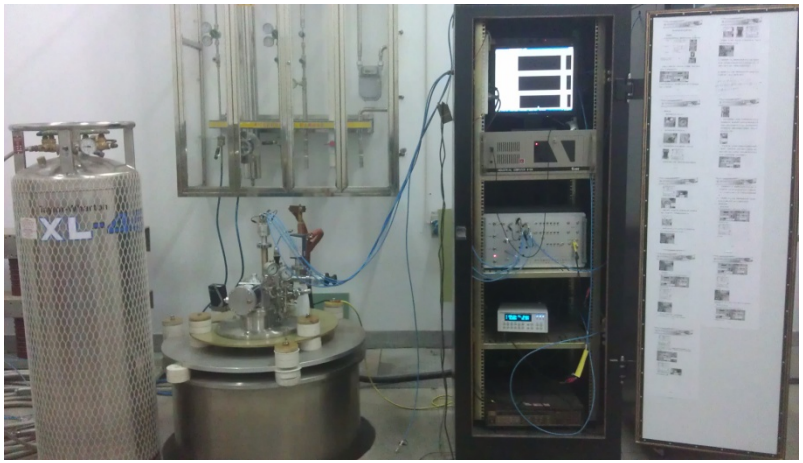
Monitoring and the Control system



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.

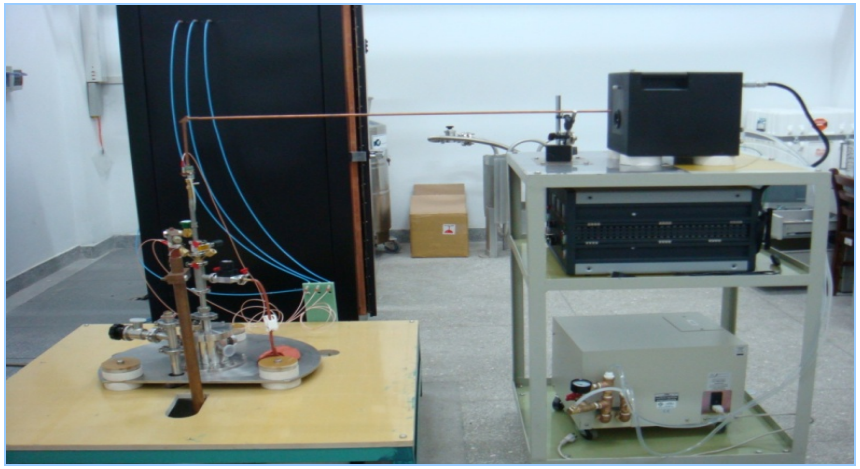
Developed 7 measurement stations

➢Magneto-Optics



➢Transport and Magnetization

➢Extremely Low Temperature system



➢ESR system

Applications of pulsed high magnetic field at WHMFC

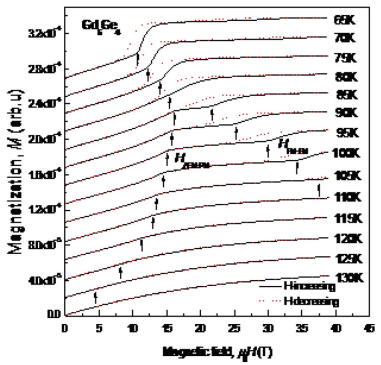
- Pulsed High Magnetic Field Facility
- Electromagnetic Forming
- Magnetic refrigiration
- Eddy current breaking
- Post magnitization

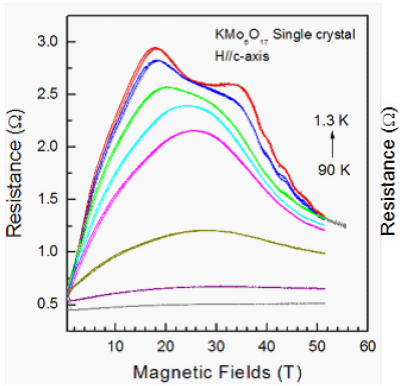
Applications of High Magnetic Field Technology

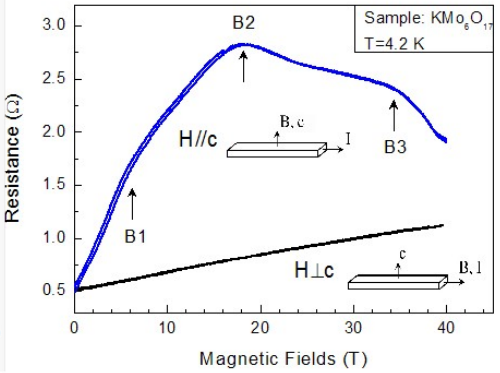
Compact Pulsed High Magnetic Field Facility

- 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.

Experimental setup







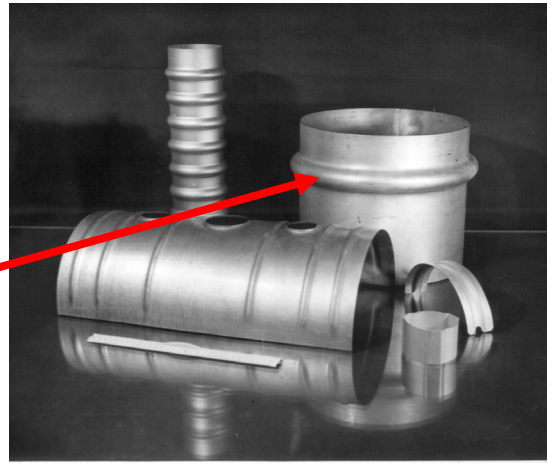
Experimental result

Development Trend of the Electromagnetic Forming

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.

Appling to form **small, thin-walled** workpieces and **local forming** only



Development trend of the electromagnetic forming

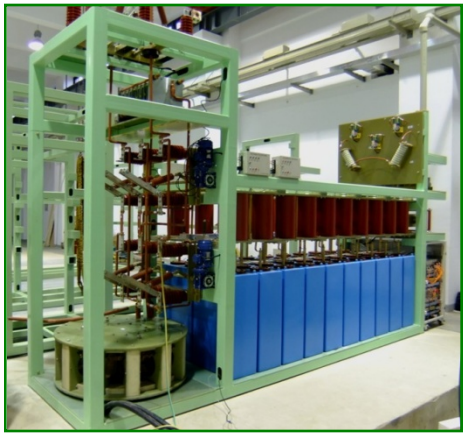
Requirements for large deformation parts forming

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

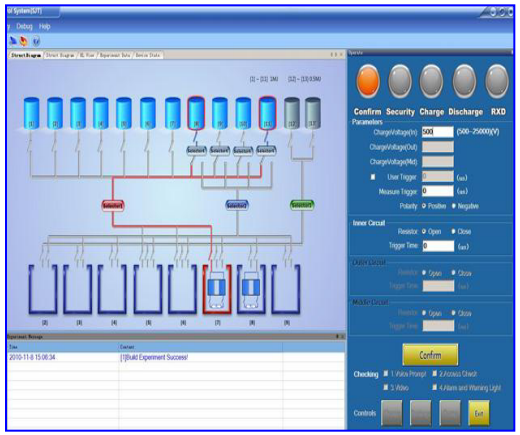
Foundation for Stic-Must-PMF

- 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 .

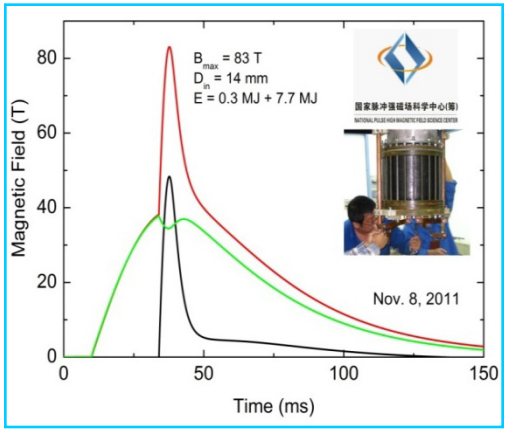
83T two-stage pulsed magnet



1000kJ single module power

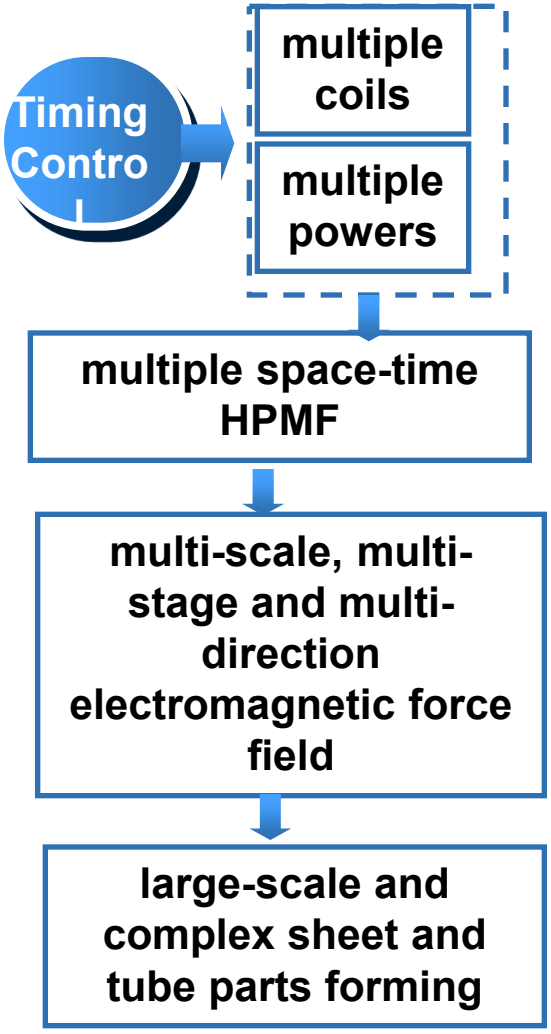


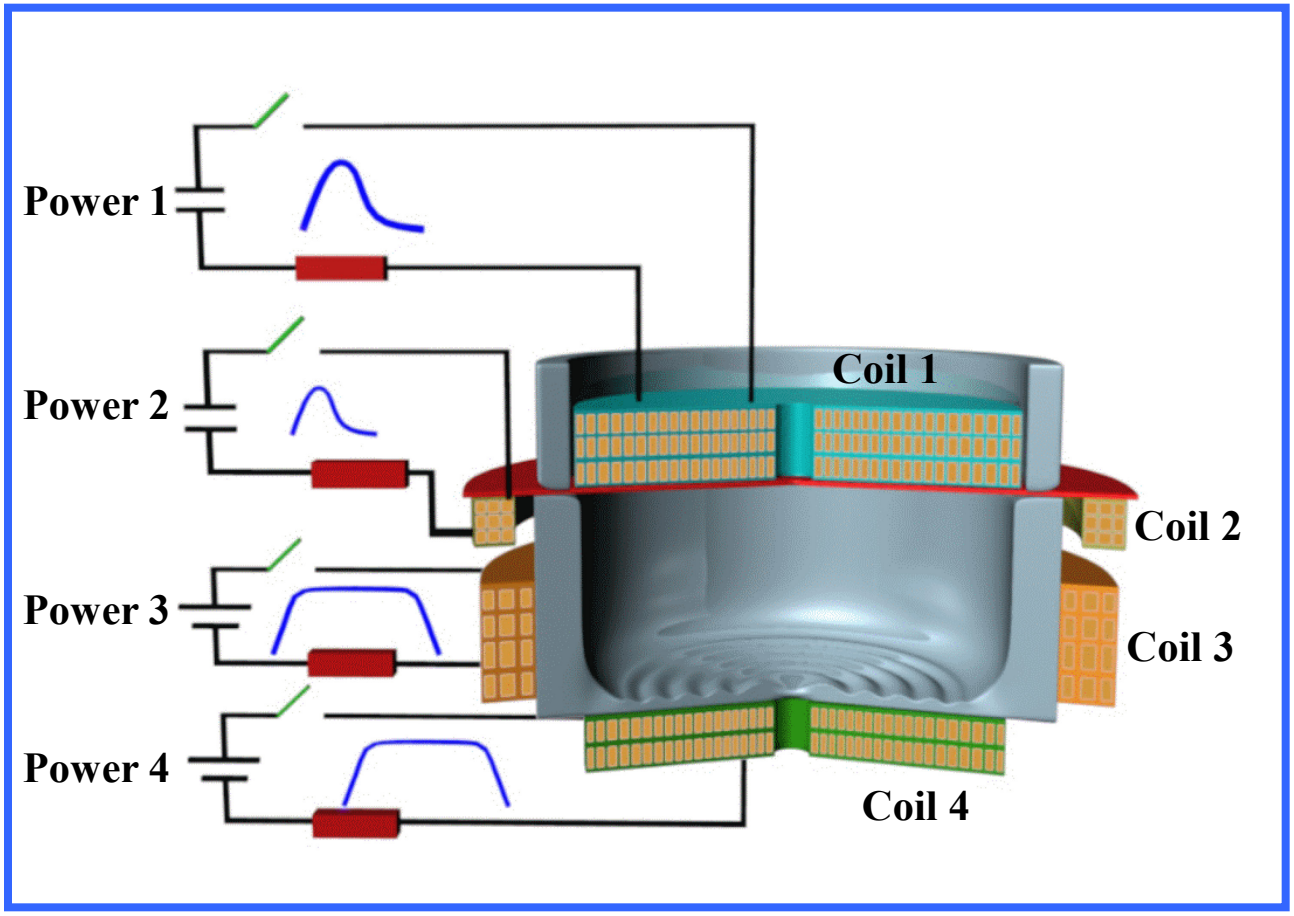
Multi-module Timing Control system



Magnetic field shape measured in the two-stage 83T pulsed magnet

Concept of Stic-Must-PMF Forming Technology

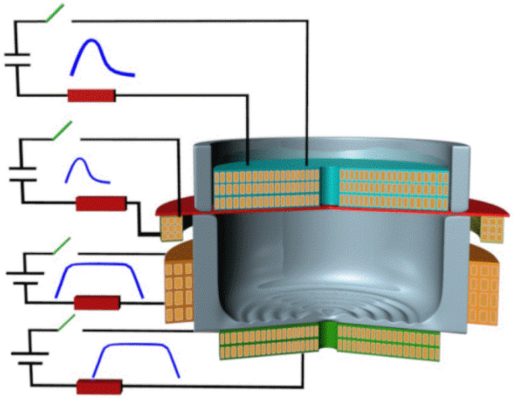




Schematic illustration of the multiple space-time PHMF deep drawing forming system

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

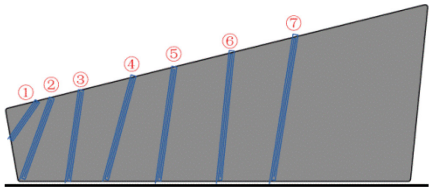
Potential Applications



- Multiple coils
- Combination long-pulse coil with short-pulse coil
- Multiple power sources

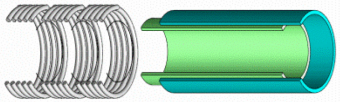
large-scale sheet
Plastic flow forming

Stic-Must
-PMF



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

large-scale panel
internal stress
adjustment and control



- High strength coil
- Continuous discharge coil

abnormity tube
Local flow and interface
connection

Challenges to the Forming Equipment

- Multi-stage and multi-direction magnetic field distribution
- Electromagnetic coupling among multi coils

  (Magnetic force among multi coils)
- Complex Interrelation between the magnetic field and materials

  (Skin effect、magneto-resistance effect)

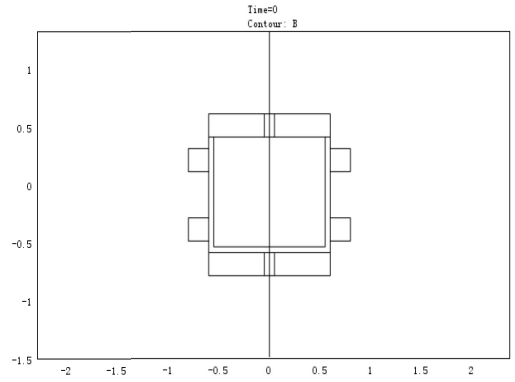
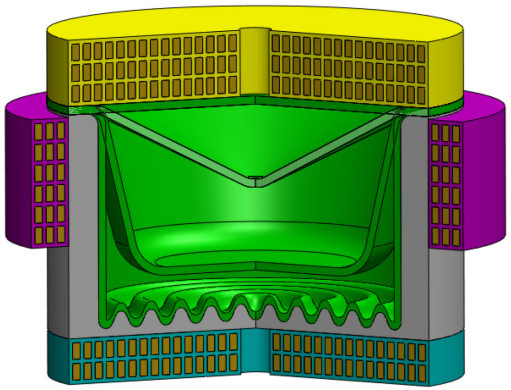
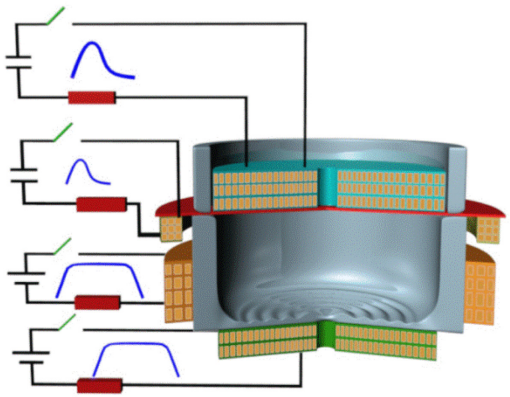
⇒ **Difficulties for optimal design of coils strength and arrangement**

How to generate the Space-Time-Controlled Multi-Stage pulsed magnetic field ?

Technological Difficulties

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

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

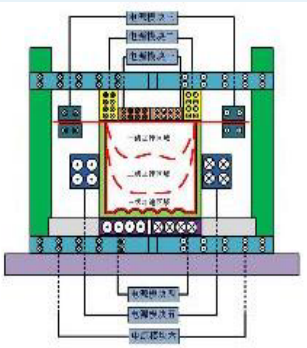
- **The effective regulation of the magnetic field and electromagnetic force for the multi-stage and multi-direction PHMF system**
- **The magnetic field penetration, eddy current distribution and the energy conversion law involved in the forming of complex structures**
- **Modeling and design criteria 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

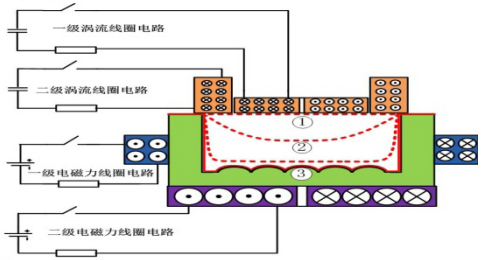
Major facility prototype

Electromagnetic parts design

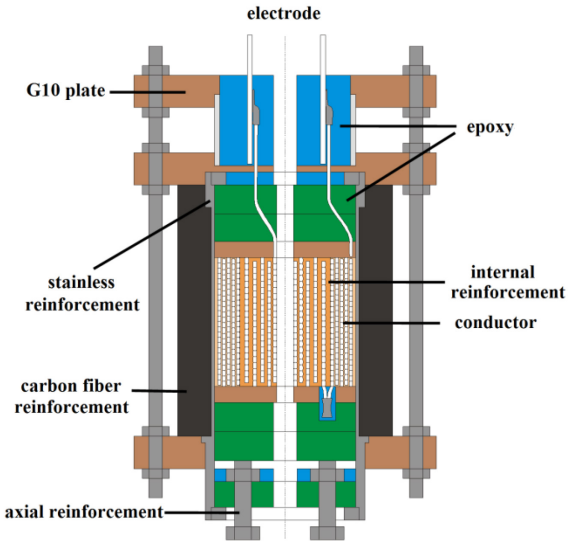
Theoretical analysis

Forming concept

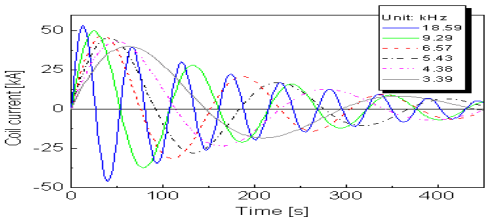
- ✓Experiment test platform
- ✓Experimental Verification of process parameters
- ✓Model calibration and modification



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



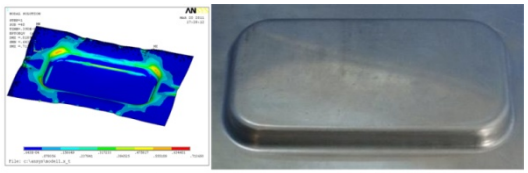
- ✓Magnetic field distribution
- ✓Forming force distribution
- ✓Energy conversion
- ✓Work-piece motion law



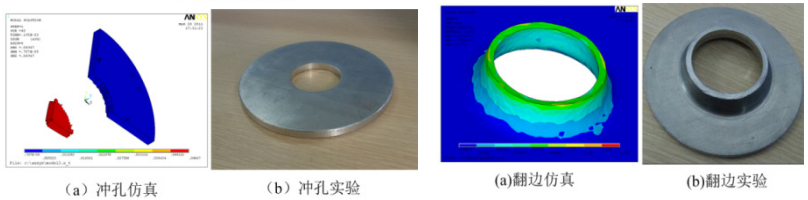
Recent progress at Pulsed Magnetic Field Forming

1. Electromagnetic Forming Equipments

- WHMFC has built a 2mF/8kV/20kA electromagnetic forming equipment, and researched the electromagnetic forming, hole flanging, and cutting using the equipment.



（a）方盒拉延仿真　（b）方盒拉延实验



（a）冲孔仿真　（b）冲孔实验　(a)翻边仿真　(b)翻边实验

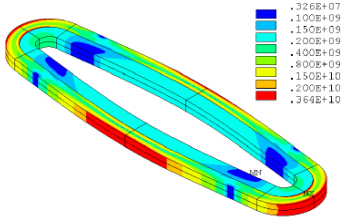


Fig. 8. von Mises stress distribution of the race-track coil with only hoop reinforcement. The maximum von Mises stress is 3.64GPa, when coil current is 14 kA, and peak field reached is 7.1 T.

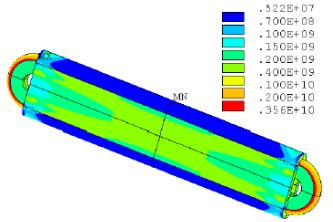


Fig. 9. von Mises stress distribution of the race-track coil with hoop and traverse reinforcement. The maximum von Mises stress is 3.56 GPa, when coil current is 55kA, and peak field reached is 28.3 T.

Electromagnetic Forming Equipment

EMF simulations and Formed Workpieces

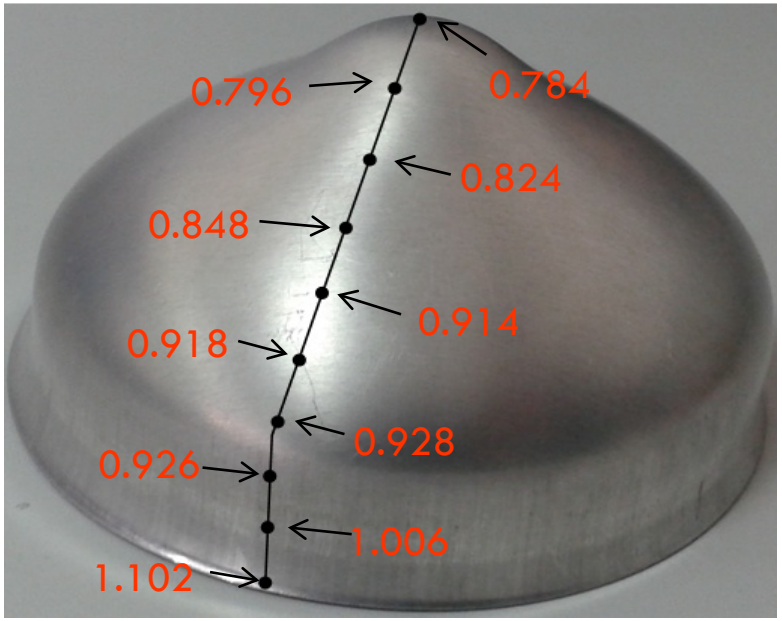
Coils Optimization

Recent progress at Pulsed Magnetic Field Forming

2. Plastic Flow in the Electromagnetic Forming Process

- 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！