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Plenary presentation 4PL_02 given at MT24; Seoul, Korea, October 18 to 23, 2015.

Water Cooled Resistive Magnets at CHMFL

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High Magnetic Field Laboratory of the Chinese Academy of Sciences

MT 24, Plenary Session 6, Seoul, Korea

2015-10-22

Outline

1. Brief Introduction of CHMFL
2. Water Cooled Resistive Magnets at CHMFL
3. Summary
4. Perspective
5. Acknowledgement

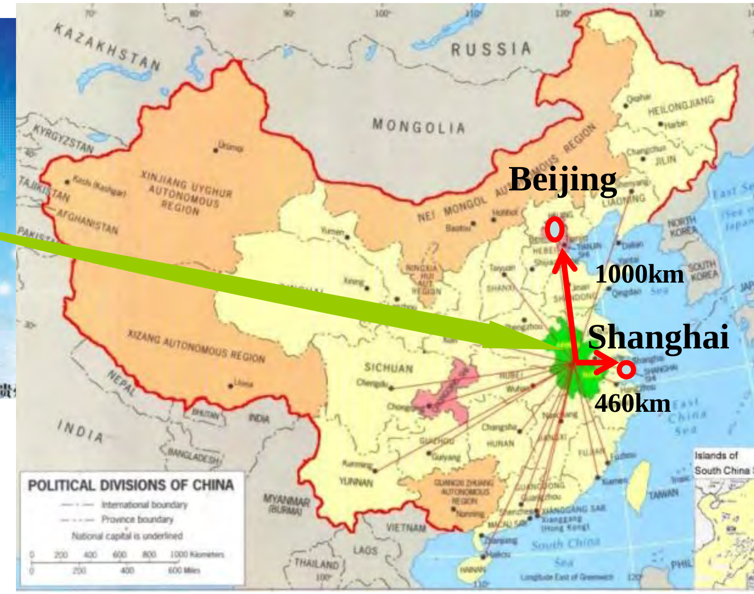
1. Brief Introduction of CHMFL

G.I. Kuang, B.J. Gao, Y.H. Zhang, N. Qiu, X.N. Liu, X.D. Zhang, Z.R. Ouyang, Z.C. Wu, Q.L. Wang, Q.Y. Lu, J.F. Wang, K. Zhong, W.G. Chen, L. Pi

- The Steady High Magnetic Field Facility (SHMFF) was founded by the National Development and Reform Commission of China (NDRC) in 2008;
- The Project is undertaken by the High Magnetic Field Laboratory of the Chinese Academy of Sciences (CHMFL).

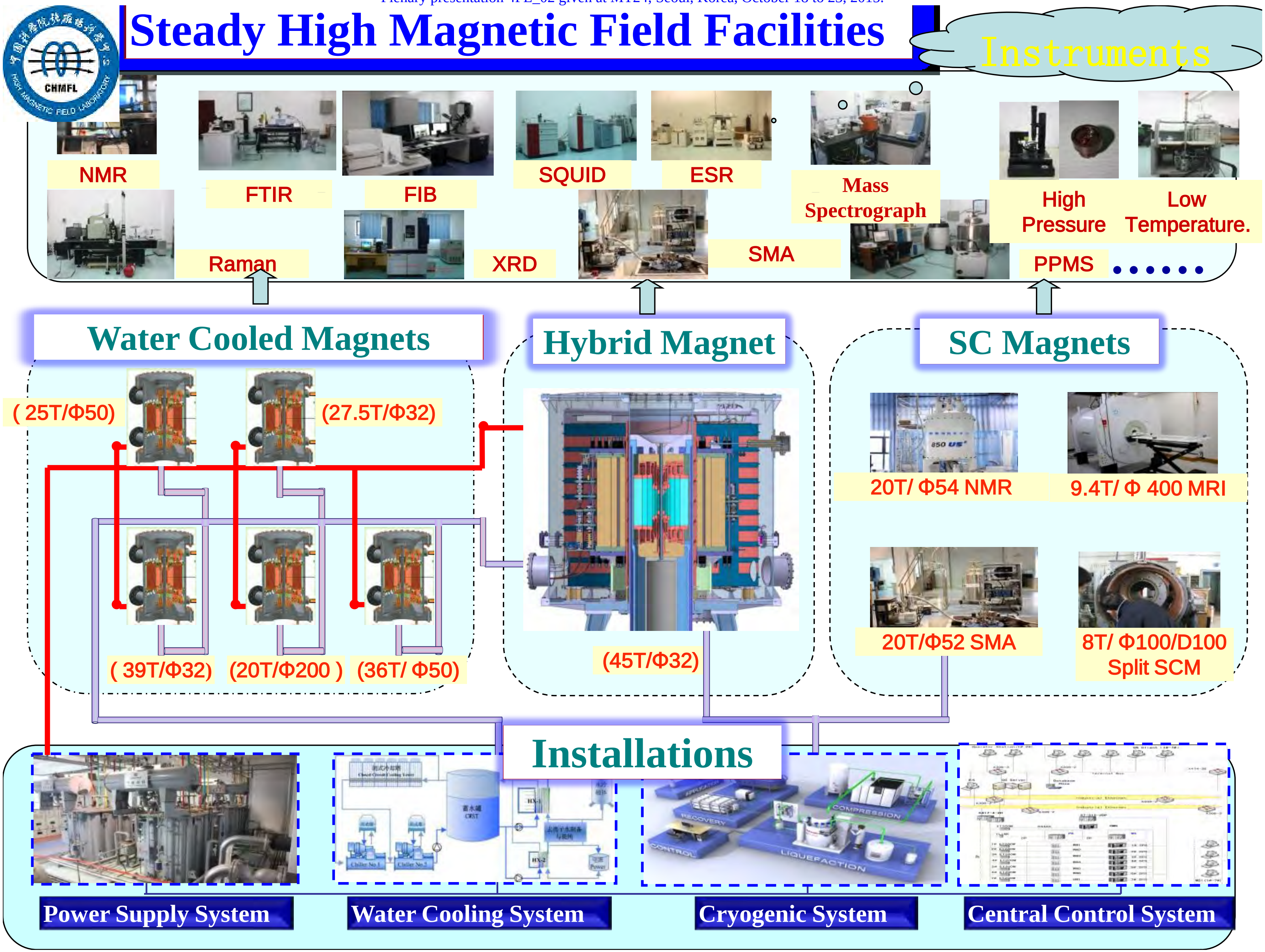
Where is CHMFL ?

Science Island *Anhui Province* *P. R. China*

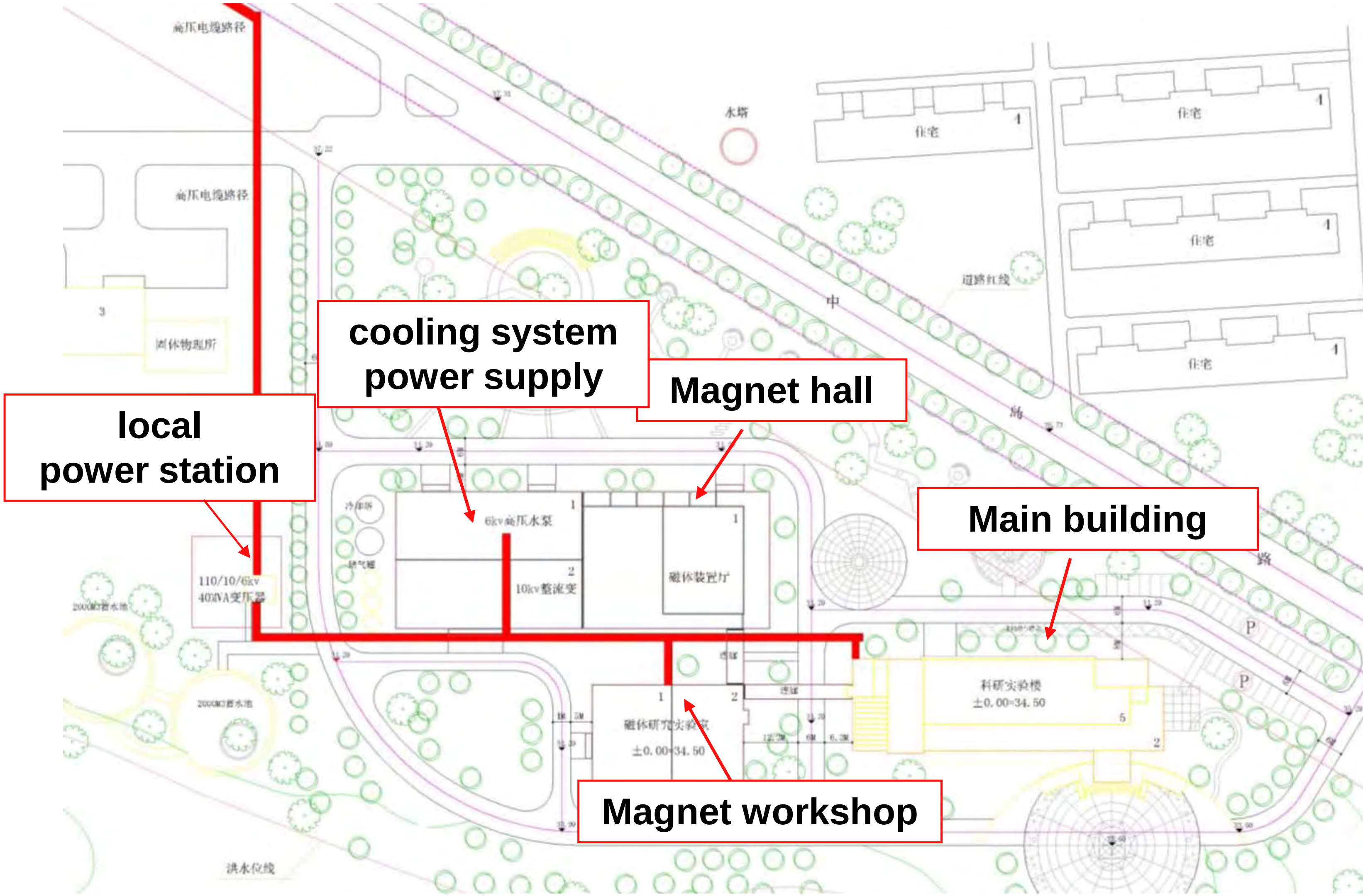


Science Island ---- a very beautiful peninsula!

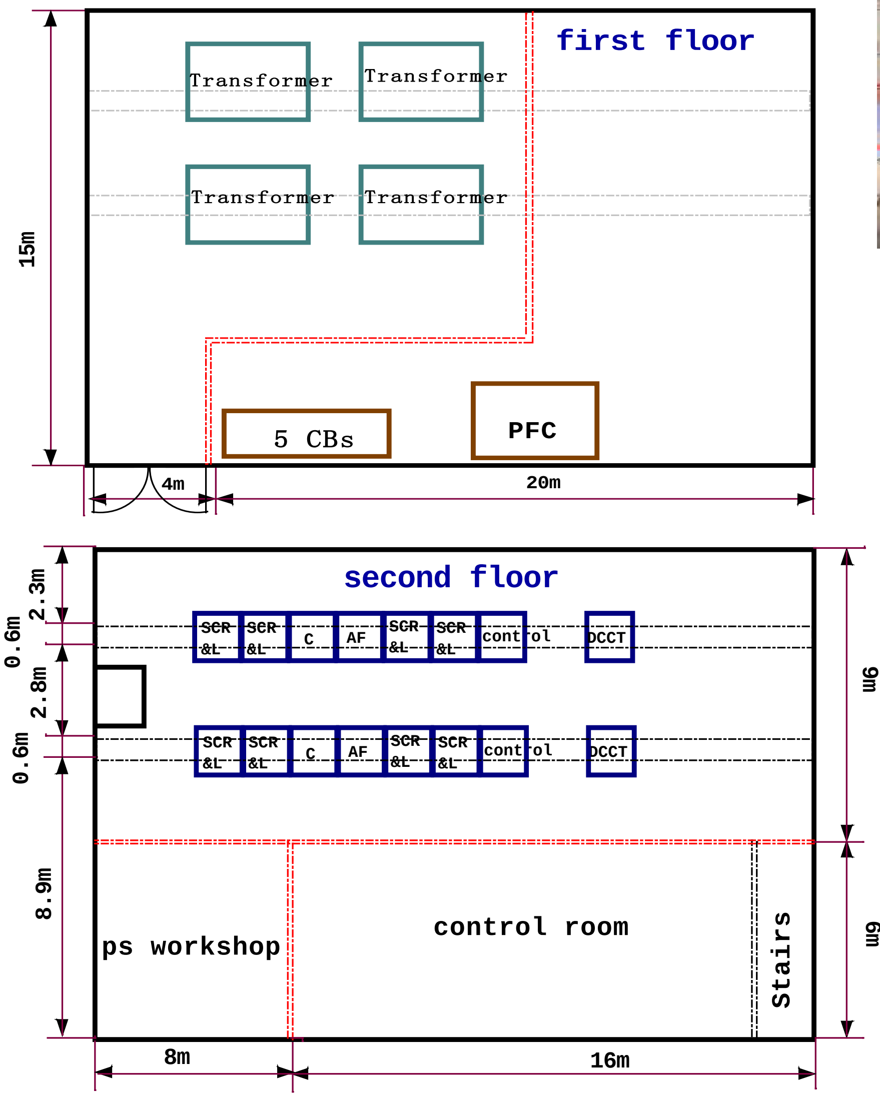
Area: 2.6 km2

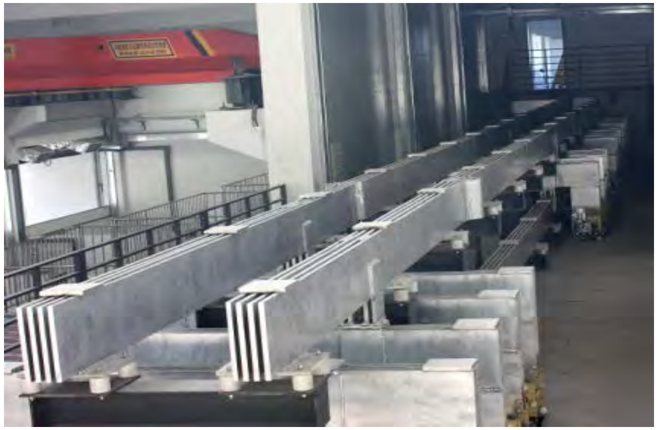

Steady High Magnetic Field Facilities
CHMFL
Instruments
NMR
FTIR
FIB
SQUID
ESR
Mass Spectrograph
High Pressure
Low Temperature.
Raman
XRD
SMA
PPMS
......
Water Cooled Magnets
Hybrid Magnet
SC Magnets
(25T/Φ50)
(27.5T/Φ32)
(39T/Φ32)
(20T/Φ200)
(36T/ Φ50)
(45T/Φ32)
20T/ Φ54 NMR
9.4T/ Φ 400 MRI
20T/Φ52 SMA
8T/ Φ100/D100 Split SCM
Installations
Power Supply System
Water Cooling System
Cryogenic System
Central Control System

Layout

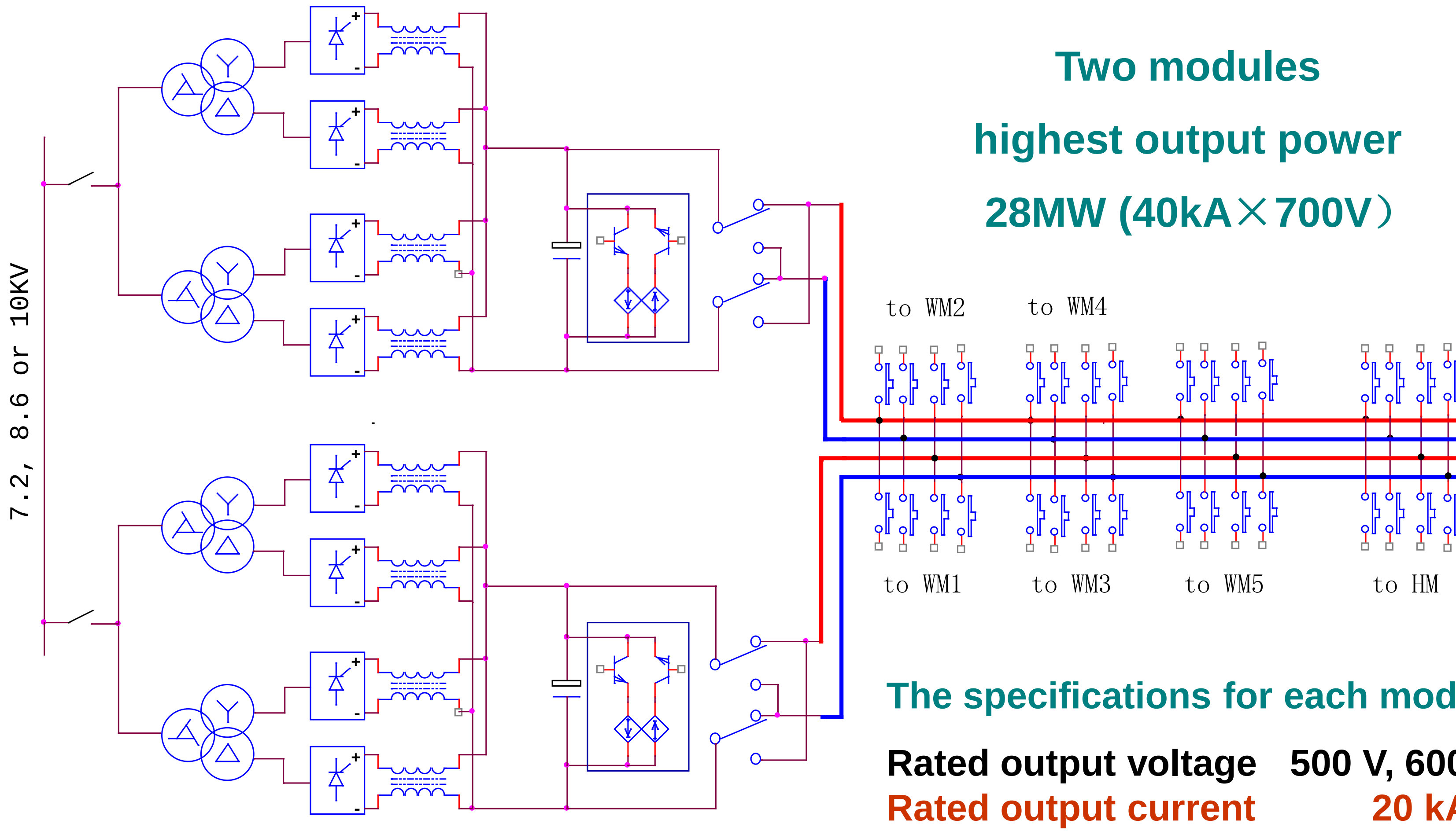

cooling system power supply
Magnet hall
local power station
Main building
Magnet workshop

A. power supply modules Installations





Configuration of the Power Supply System



Two modules

highest output power

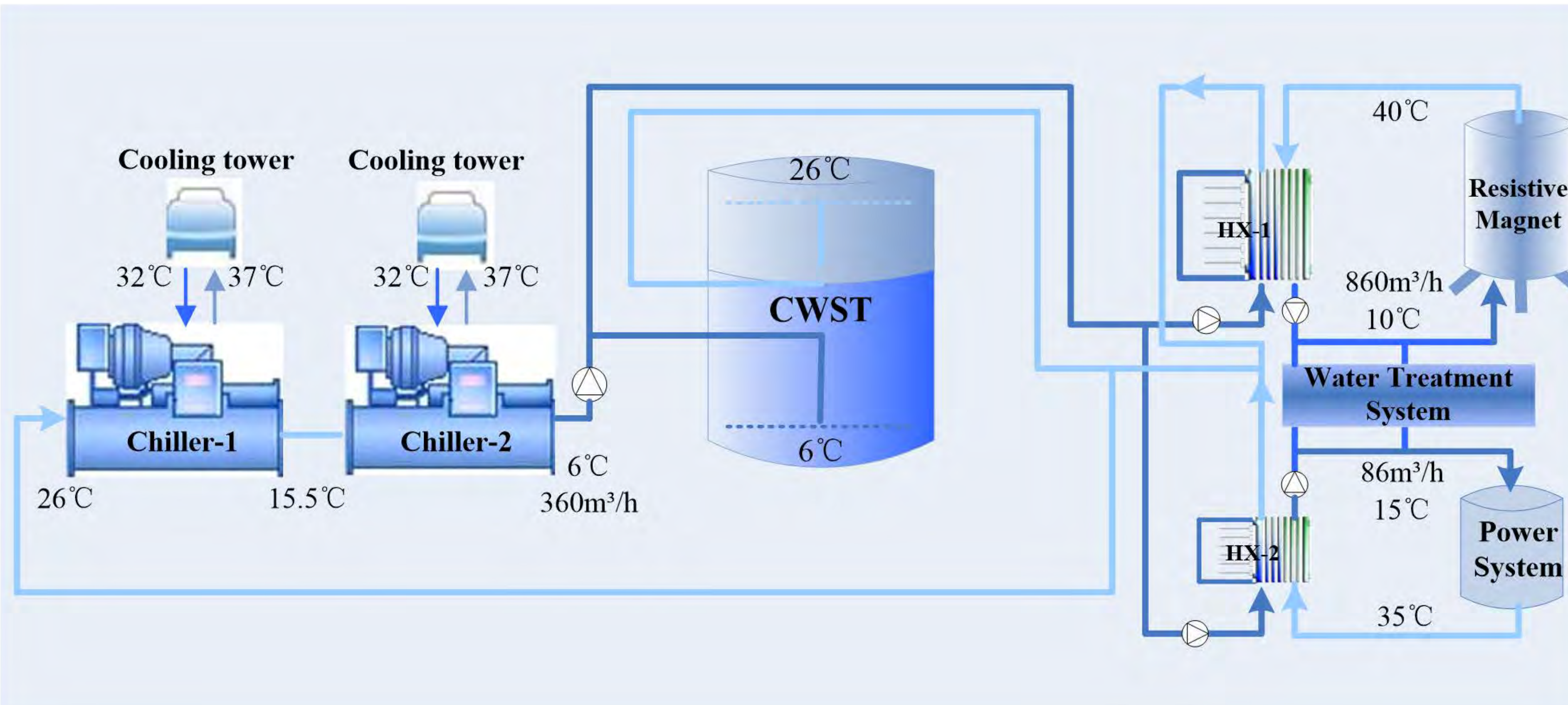
28MW (40kA×700V)

The specifications for each module:

Rated output voltage	**500 V, 600V, or 700V**
Rated output current	**20 kA**
Ripple and noise	**10 ppm**
Stability(4 hours)	**10 ppm**
Efficiency	**>90%**

B、Water cooling system

Flow Chart



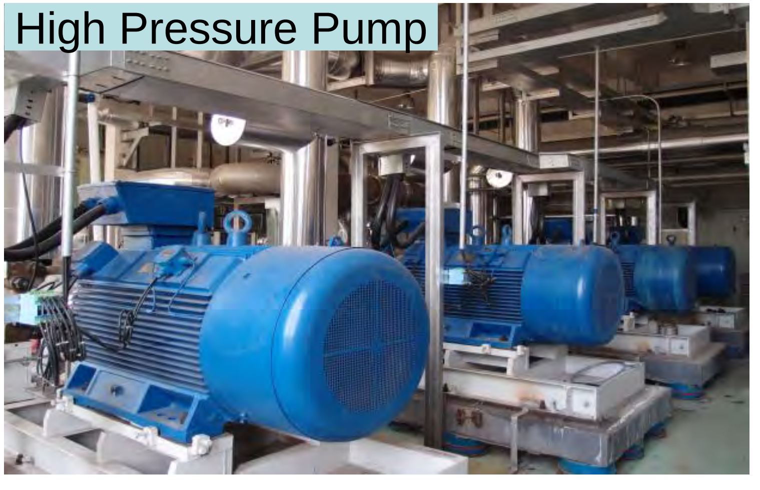
B、Water cooling system

Main Parameters

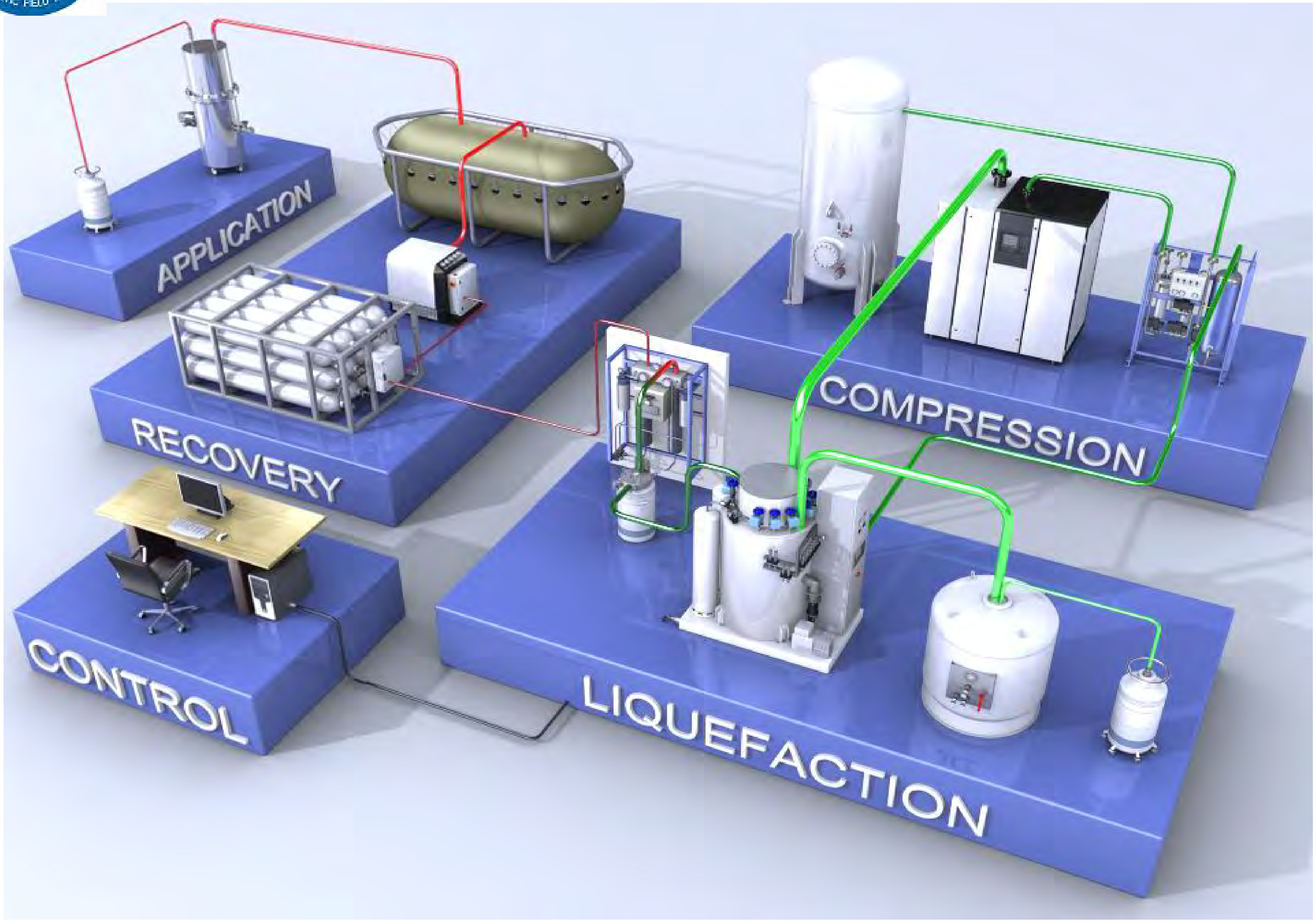
Water resistivity at magnet entrance	≥15MΩ·cm
Dissolved O_2 content in Magnet loop	≤10ppb
Magnet loop max flow	$860m^3/h$
Max water pressure at magnet entrance	3MPa
Water temperature at magnet entrance	10℃
Max water temperature at the export of magnet	40℃
Max taken heat energy	20MW / 28MW
Refrigeration power of the chillers	8MW
Chilled water storage power	70MW
Continue run time in 20 MW heat energy case	≤6 hour / day

B、Water cooling system

Main Equipment



C. Helium Cryogenic System



C. Helium Cryogenic System

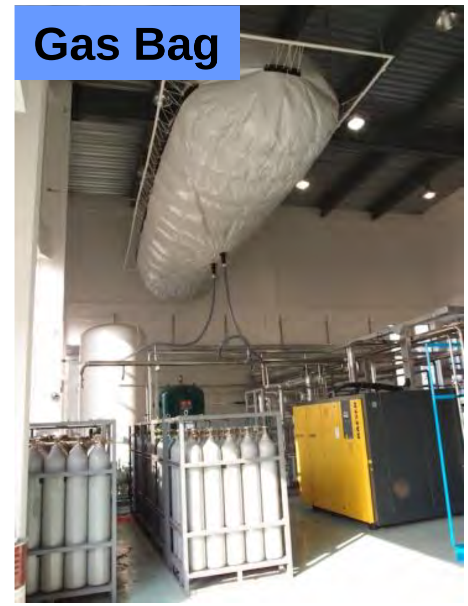
Technical Characteristics

Liquefaction rate	> 110 L/h@1.3 bar
Refrigeration	> 360 W@4.5 K
Recovery compressor	75 m^3/h
Helium gas storage	6100 m^3
LHe storage	6600 L
LN2 storage	30 m^3

C. Helium Cryogenic System

Helium Refrigerator

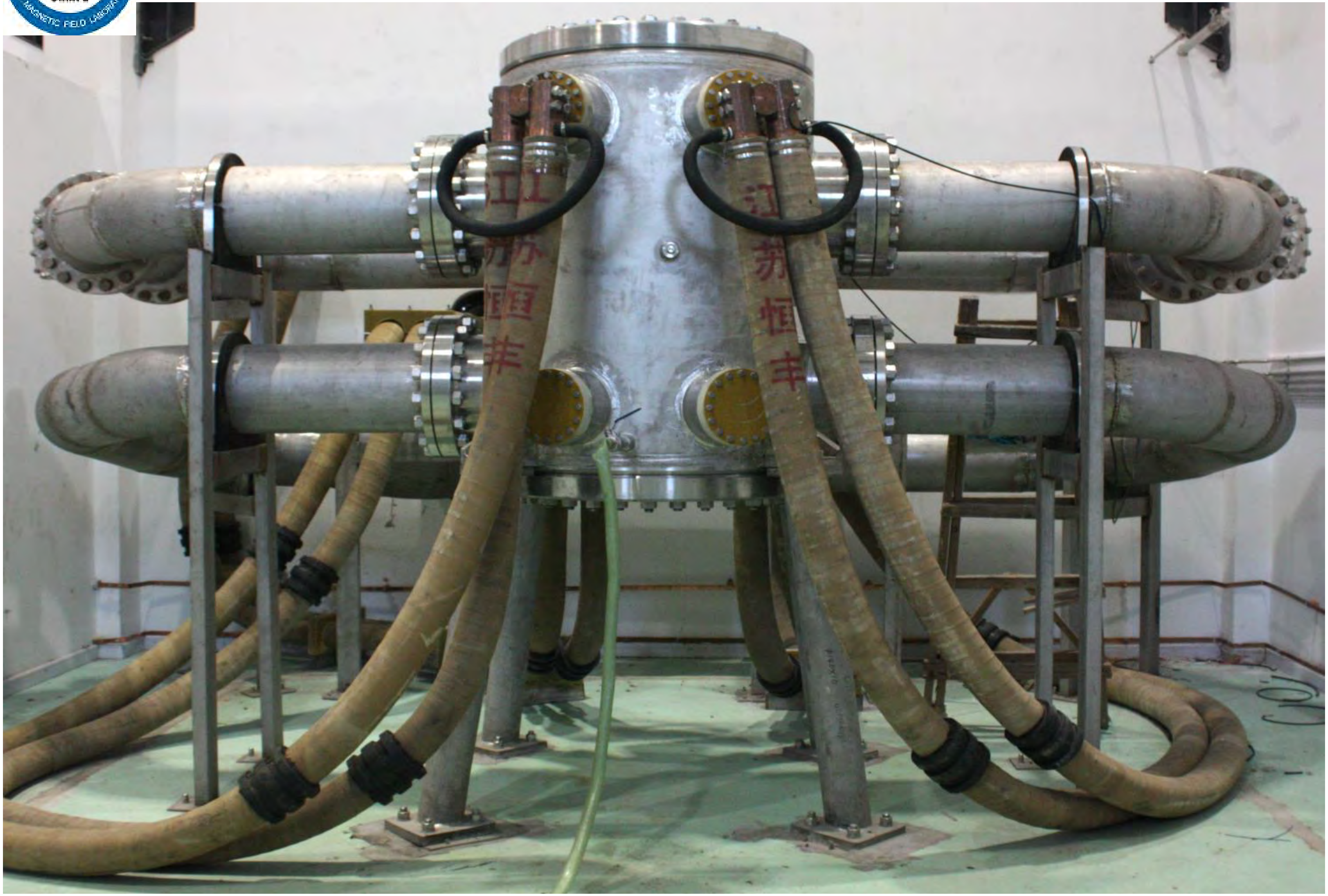

Storage Tanks


Gas Bag

LHe Dewar

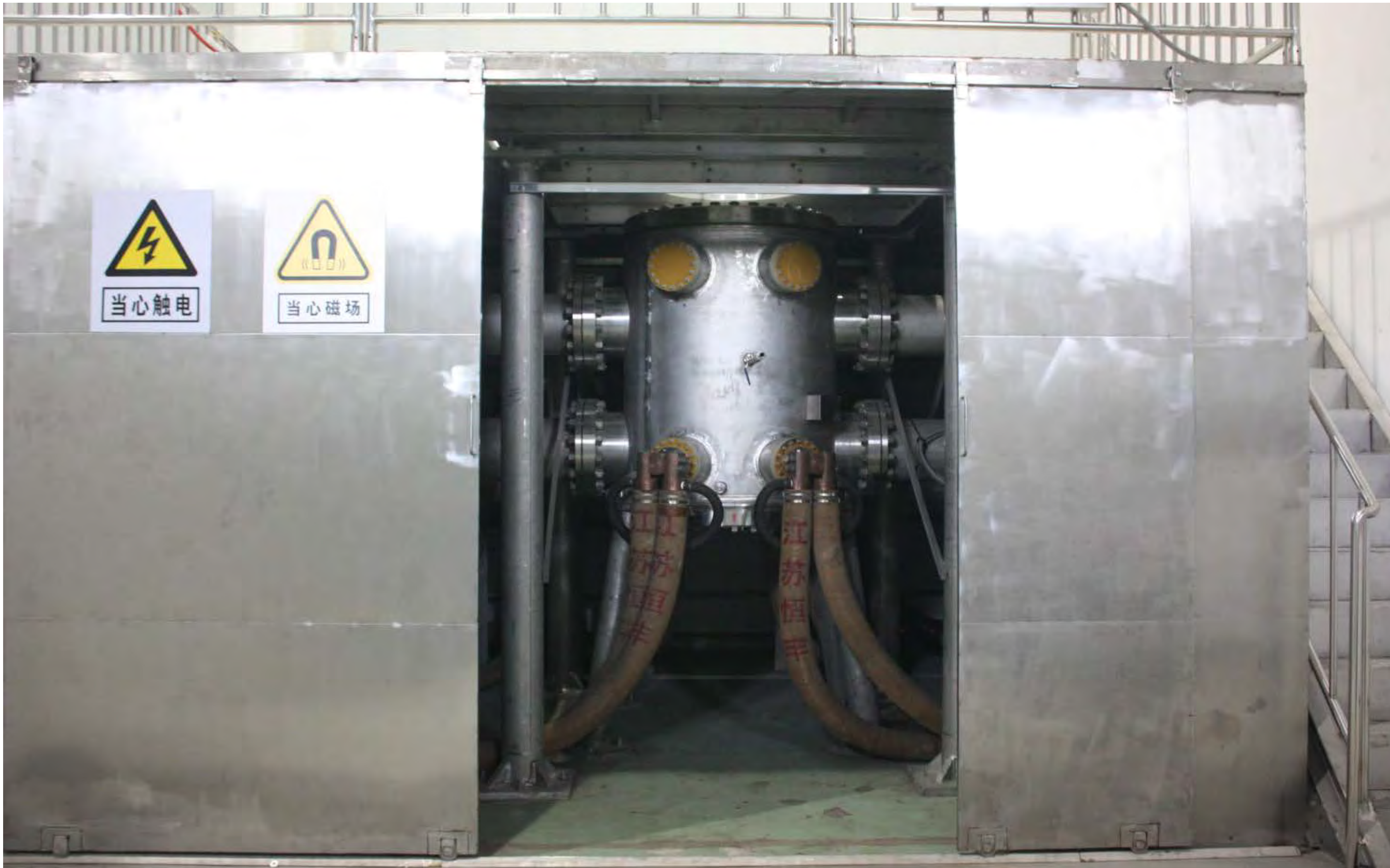
Compressor

Water Cooled Resistive Magnet Facility



Cell 1: WM1 Magnet Facility
38.5 T, 32 mm

Cell 2: WM2 Magnet Facility
25 T, 50 mm, 50 ppm



Cell 3: WM3 Magnet Facility
19.5 T, 200 mm

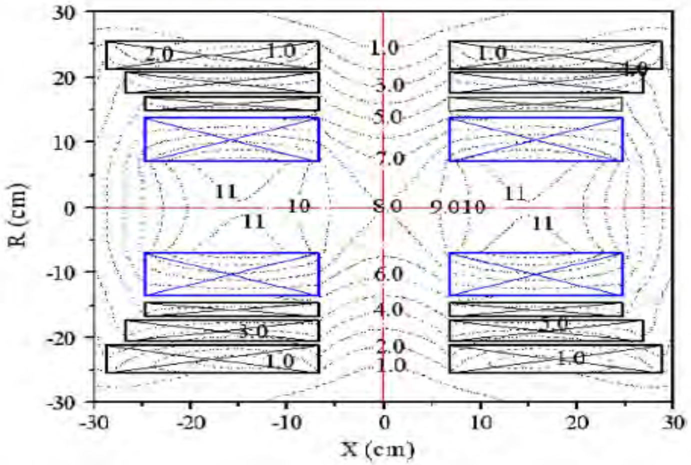
Cell 4 : WM4 Magnet Facility 27.53 T, 32 mm

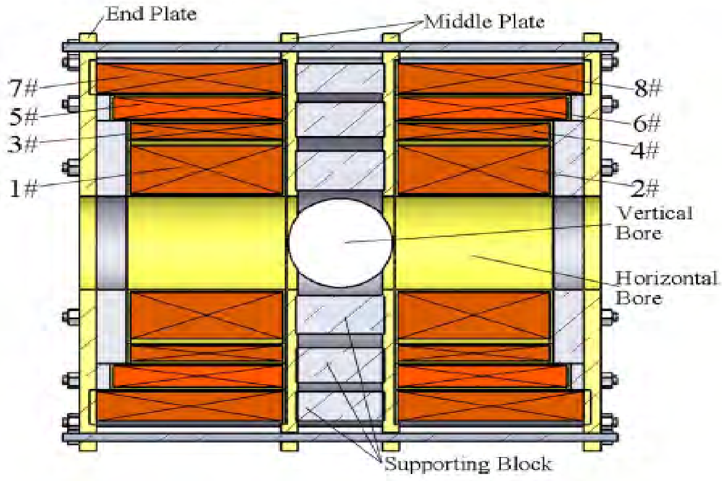
Cell 5: WM5 Magnet Facility
35 T, 50 mm

SM1
8-T Superconducting Split Magnet System

✓Configuration

The magnet is composed of six NbTi low temperature superconducting coils, which generate 5.5-T central magnetic field and two Bi2223/Ag high temperature superconducting (HTS) insert coils, which generate 2.5-T central magnetic field and assembled in the form of split coil groups. The Magnet has a 136-mm split gap to accommodate the crossing warm bore of 100 mm in diameter. The magnet system is cooled by two GM cryocoolers.





SPECIFICATIONS of SM1

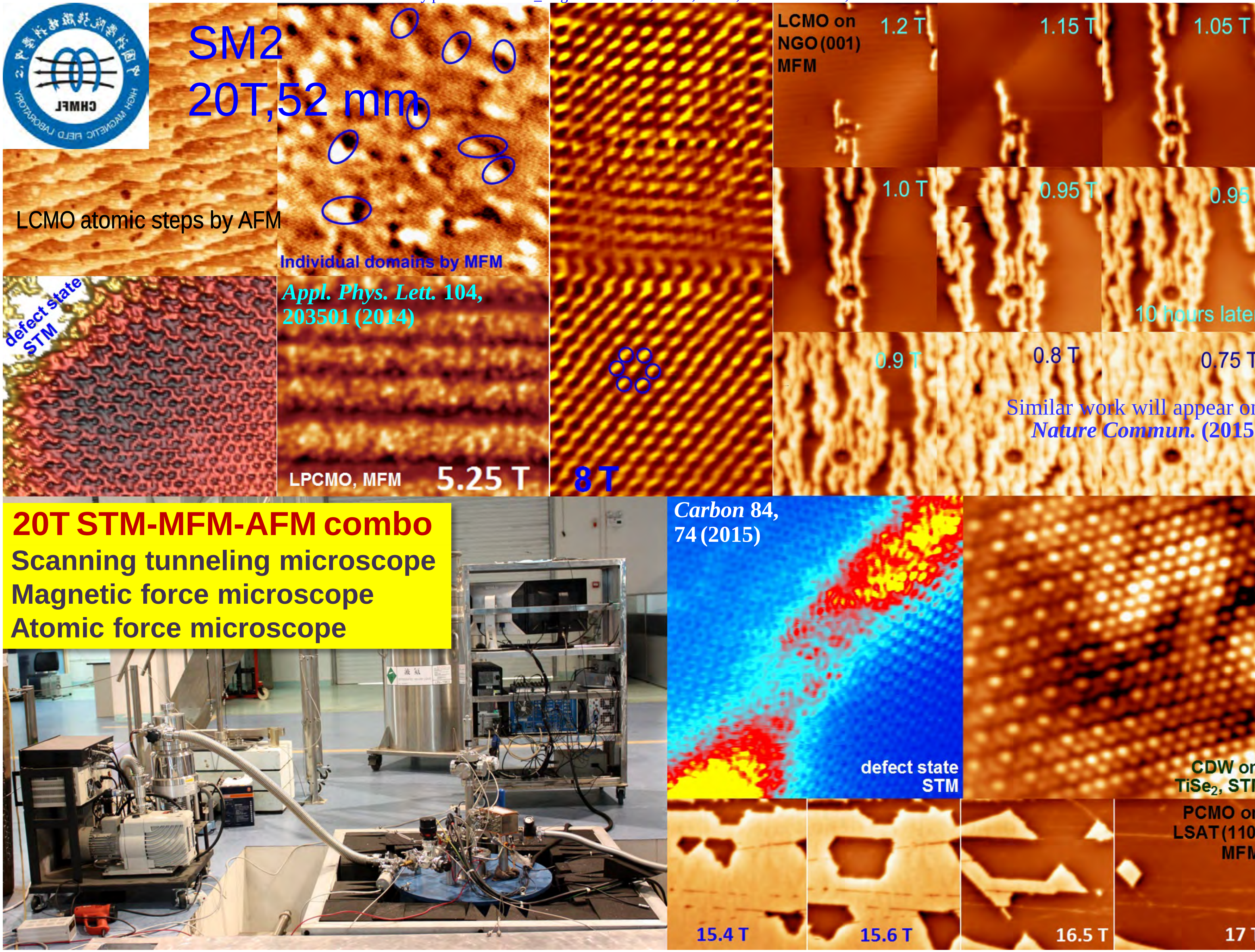
Magnet

Magnet Diameter	Inner 134 mm Outer 596 mm	**Operating Current**	HTs Coil NbTi Coil	200A 136A
Central Magnetic Field B0	8 T	**tored Energy**		1.38 MJ

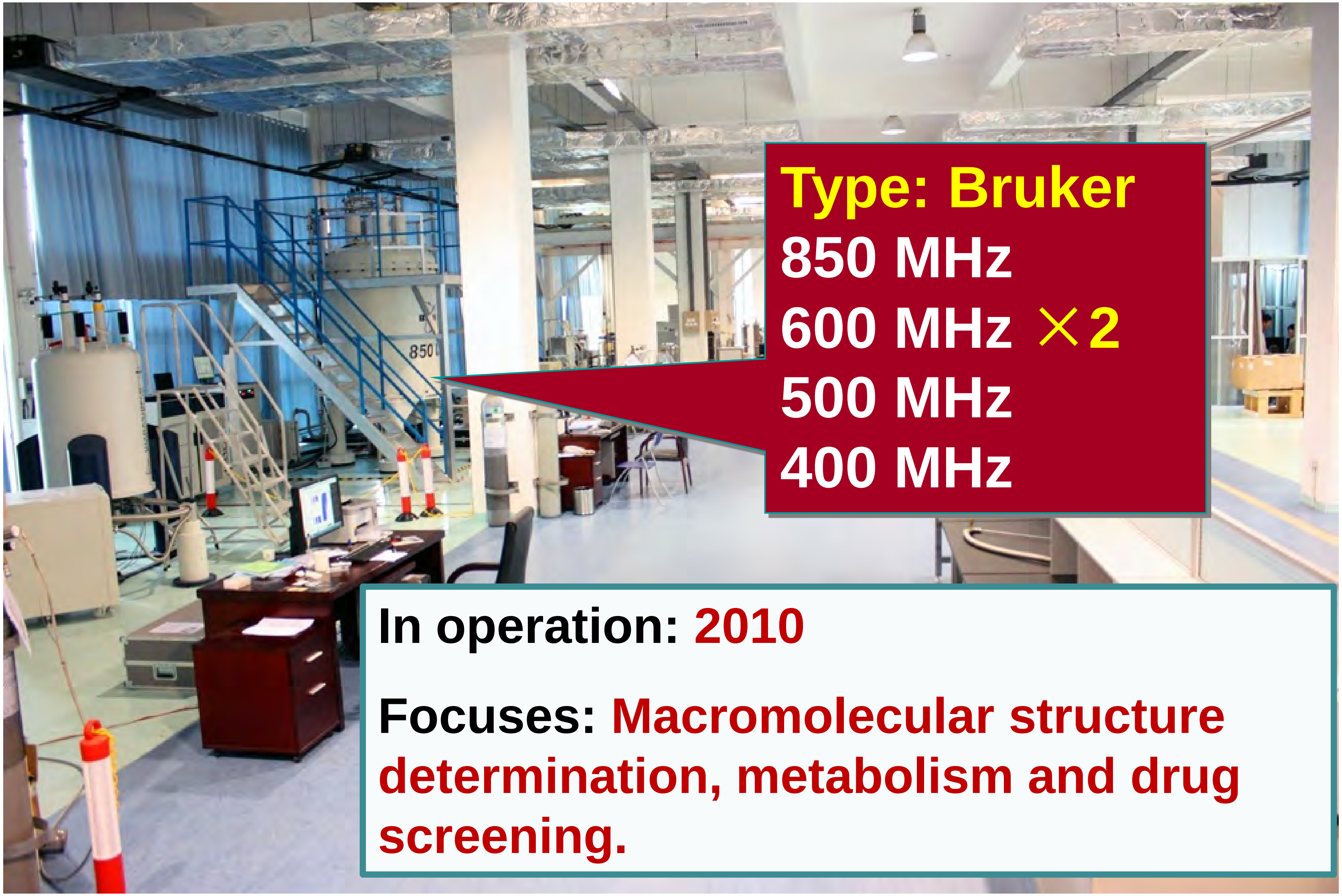
Coils

	Conductor Material	Wire Size (mm)	Insulation	Ic (A)	I.D (mm)	O.D (mm)	Height (mm)	Total turn	Current density (A/mm^2)
1#-2#	Bi2223/Cu	4.3×0.27	kapton	145 (s.f,77K)	140	274	180	5236	94.73
3#-4#	NbTi/Cu	1.0×1.46	Formvar	1400 (5T,4.2K)	290	332	180	2074	77.05
5#-6#	NbTi/Cu	0.8×1.37	Formvar	1100 (5T,4.2K)	346	407	200	4388	89.81
7#-8#	NbTi/Cu	0.78×1.38	Formvar	1000 (5T,4.2K)	421	503	220	6558	100.73

IEEE tran. Applied Superconductivity, Vol. 22, No. 5, October 2012, 4705907


SM2
20T,52 mm
LCMO atomic steps by AFM
Individual domains by MFM
LCMO on NGO(001) MFM
1.2 T
1.15 T
1.05 T
1.0 T
0.95 T
0.95 T
10 hours later
0.9 T
0.8 T
0.75 T
Similar work will appear on *Nature Commun.* (2015)
defect state STM
Appl. Phys. Lett. 104, 203501 (2014)
LPCMO, MFM
5.25 T
8 T
20T STM-MFM-AFM combo
Scanning tunneling microscope
Magnetic force microscope
Atomic force microscope
Carbon 84, 74 (2015)
defect state STM
CDW on $TiSe_2$, STM
PCMO on LSAT(110) MFM
15.4 T
15.6 T
16.5 T
17 T

SM3--Biomolecular NMR Instruments



Type: Bruker

850 MHz

600 MHz ×2

500 MHz

400 MHz

In operation: 2010

Focuses: Macromolecular structure determination, metabolism and drug screening.

SM4---9.4 T MRI

Field Strength： 9.4 T
Bore size： 400 mm
Gradient： 100/300/2000 mT/m
RF Channel： 8 Tx / 16 Rx
Iron Shield： 120 ton

Unified MRI-animal Facility






2. Water Cooled Resistive Magnets at CHMFL

B.J. Gao, L.R. Ding, Y. Zhang, Z.J. Wang, J. Li, J. Su

Magnet No.	Bore (mm)	goal Field (T)	Design Field (T)	Design Current (A)	Test result and date Field (T)	Current (A)	Power (MW)	Unif. (ppm)	Date
WM4	32	26	27.74	19800	27.53**	19700	9.98	1232	130903
WM2	50	25	25.02	32825	25.04	32910	15.0	64	150617
WM3	200	19.5	19.94	39650	19.556	39500	18.8	149	151016
WM1	32	33.	38.505	37710	38.1				140520
					38.51**	37938	25.3	582	150616
WM5	50		35.05	36820	35.02**	36820	24.12	426	140423
HWM11	32	29/40	33/44	25.4	to be testing in the spring next year				
HWM12	50	26/37	30/41	25.5					

(1) History -1

Institute of Plasma Physics, CAS, Hefei, China

- 1984-1992

A Project of CAS -- 20 T Hybrid Magnet Facility

May 23, 1992

HM 20.02 T, 32 mm

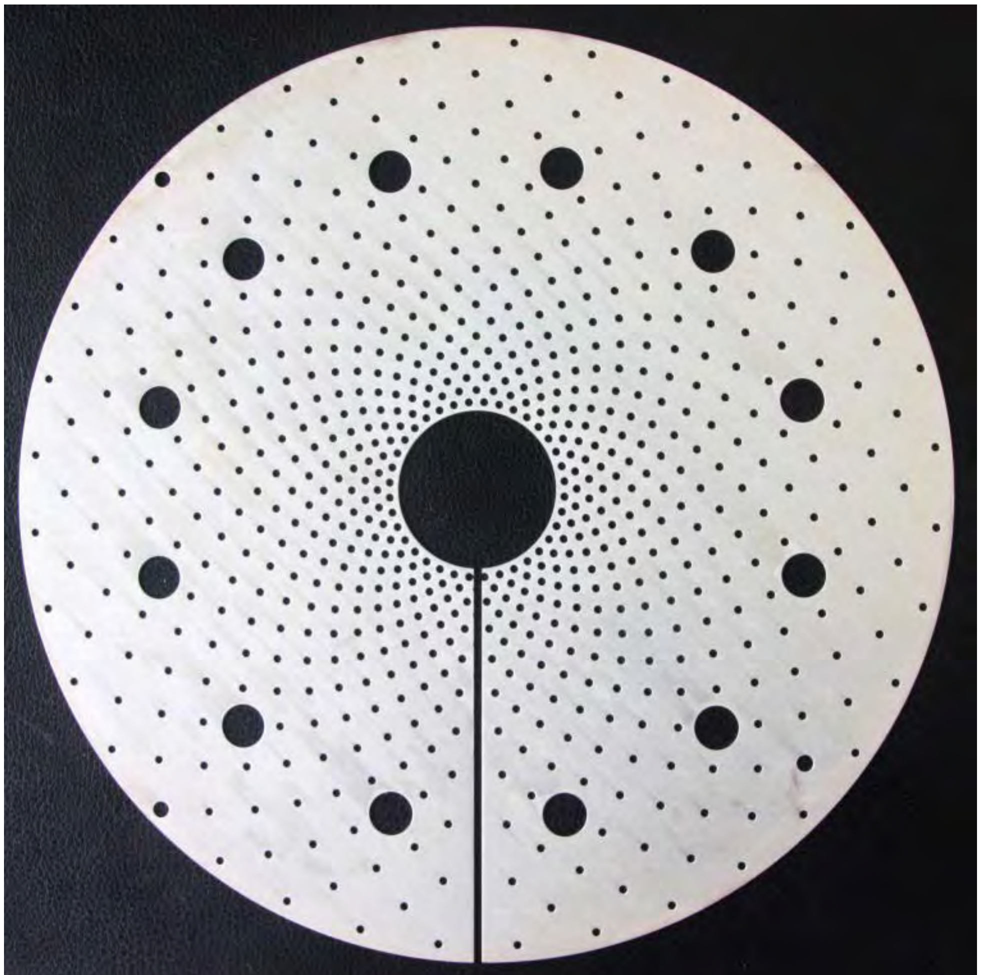
HWM 12.59 T, 32 mm

HSM 7.53 T, 266 mm

Proceeding of 9th International Conference on Magnet and Technology, Zurich, Sept. (1985), 223-225.

• Insert of 20 T Hybrid Magnet, HWM

First Water Cooled Magnet in China



Inner Diameter	38 mm
Outer Diameter	224 mm
Hight	143 mm
Conductor	Glidcop
Power	3.0 MW
Current	11444 A
Field	13.5 T

(1) History -2

NHMFL, FSU, USA

- **August 1992—July 1995 & May 1996—June 1997, GAO Bing Jun was invited by Jack and Hans, to join the team of water cooled resistive magnet.**

We invented :

A new concept of Bitter disk design

IEEE tran. On Magnetics, vol. 32, No. 4, 1996, pp 2503-2506

Florida Bitter

• Florida Bitter Facilities at NHMFL

WM 27 T, 32 mm, 35 kA,13 MW, June 1994, **New World Record**
WM 30 T, 32 mm, 35 kA,15 MW, March 1995, **New World Record**
WM 33 T, 32 mm, 39.2 kA,19 MW, Feb.1996, **New World Record**
HM 45 T, 32 mm / 31T, 66.6 kA +14T, 616 mm, Jan. 2000, **New World Record**
45 T, 32 mm / 33.6T, 72.2 kA +11.4T, 616 mm, Feb. 2001

First Magnet /3 coils / 27T Magnet

First Florida Bitter Coil A, 30 T magnet

IEEE tran. On Magnetics, vol. 32, No. 4, 1996, pp 2444-2449

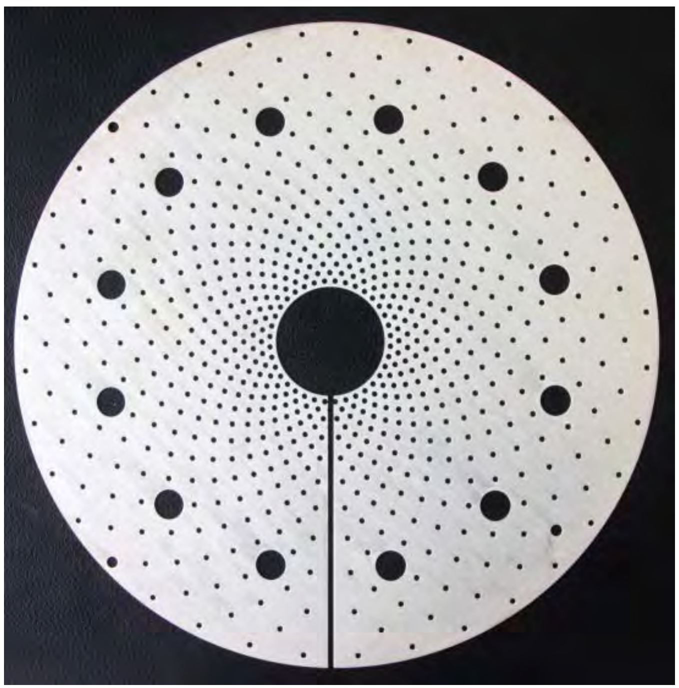
(1) History -3

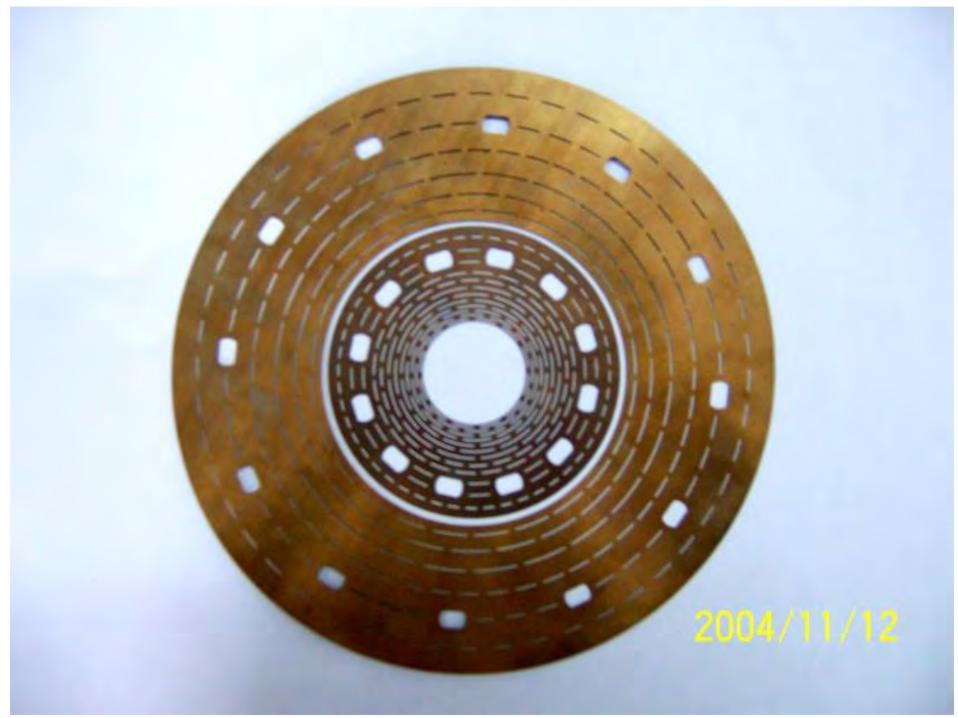
Institute of Plasma Physics & Institute of Solid State Physics

CAS, Hefei, China

- 2000-2005

A Project of CAS---R & D of Quasi-Static Mag. Field Tech.





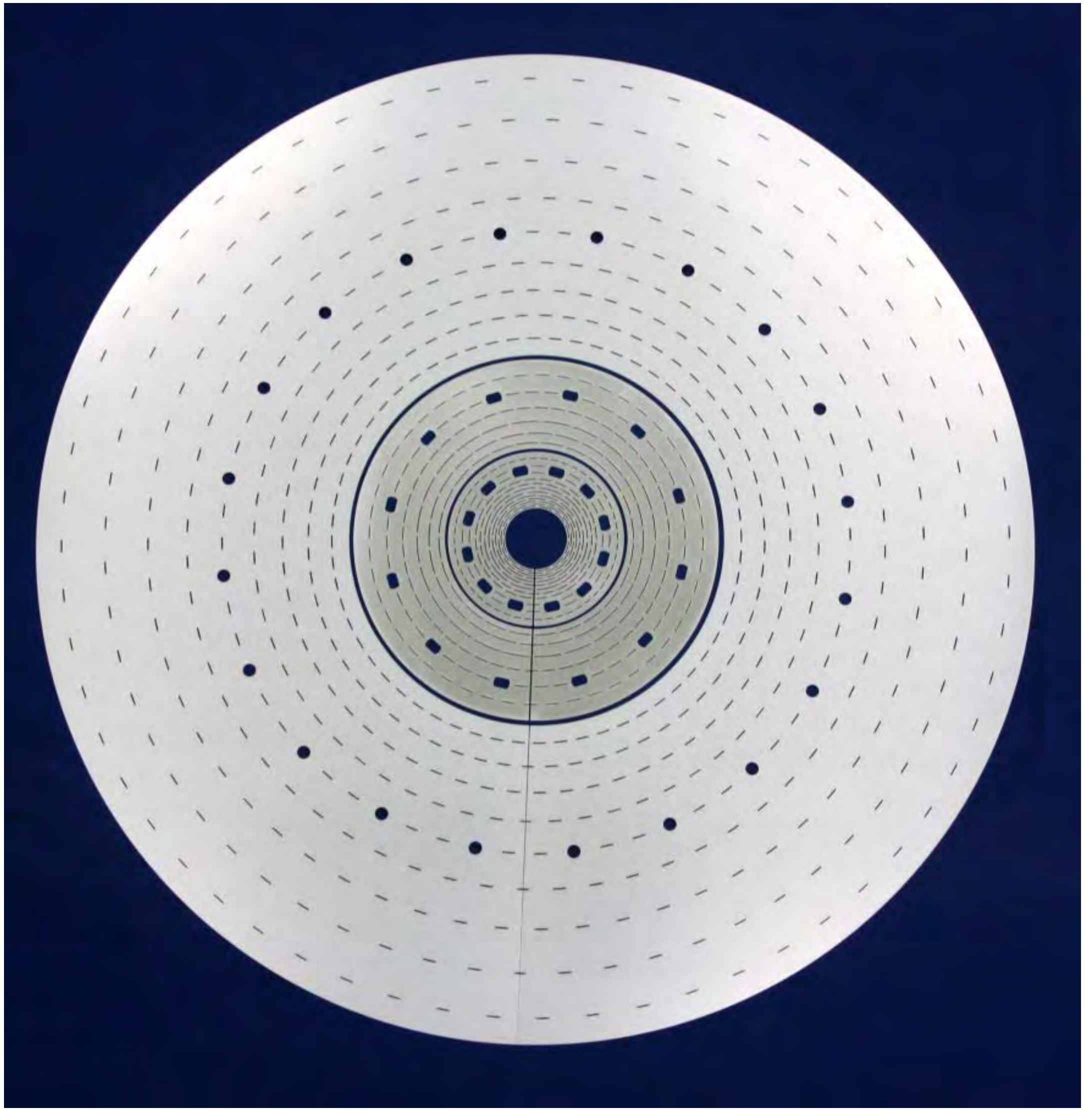
20 T, 32 mm

12.5 T / 32 mm + 7.5 T / 266 mm

25 T, 32 mm

17.5 T / 32 mm + 7.5 T / 266mm

(2) CHMFL
• WM4 / WM2 Magnets



- **WM4 Magnet**

  32 mm bore

  Bitter Disks

  Three Coils

  Inner diameter

  38 mm

  Outer diameter

  610 mm

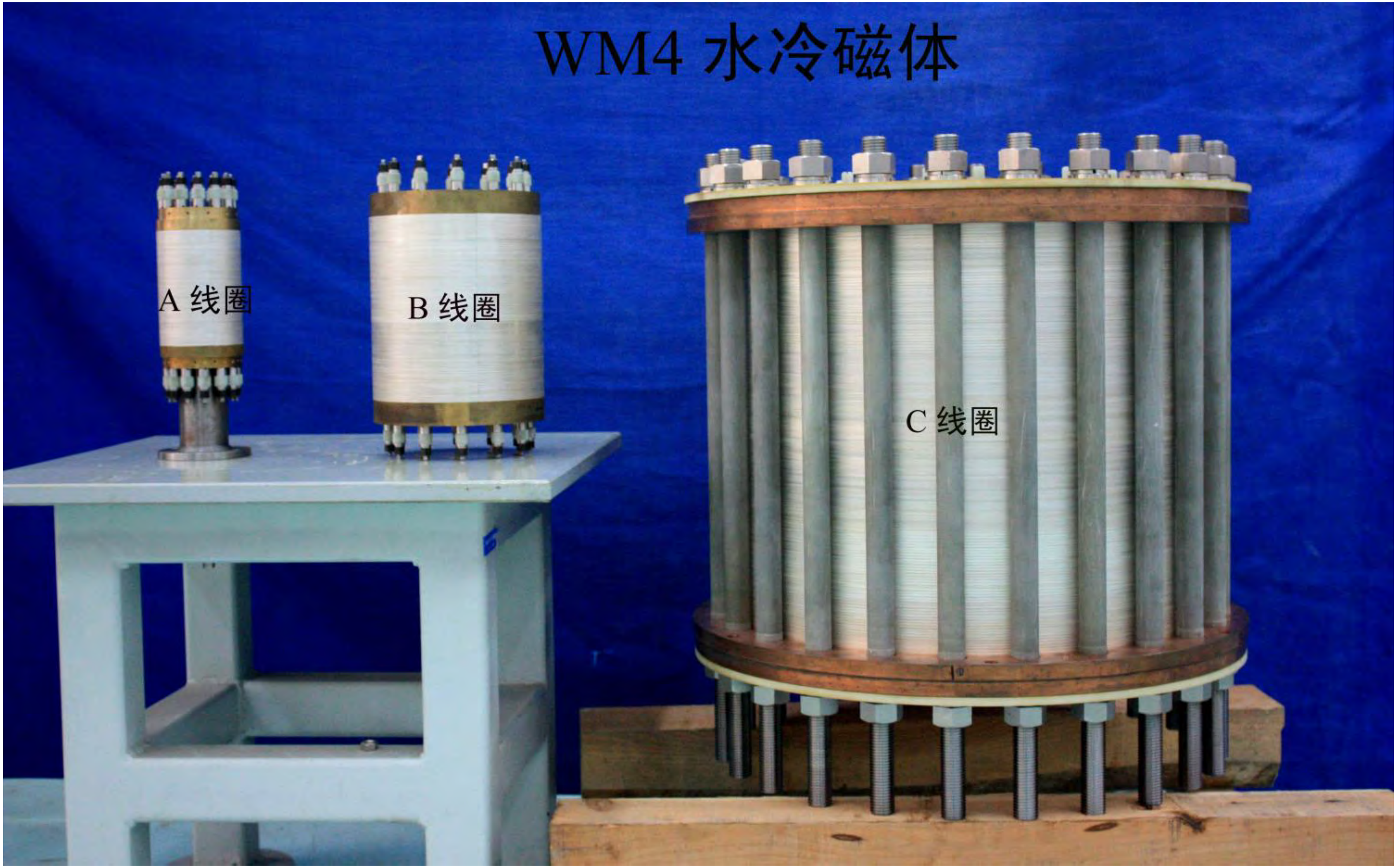
● Parameters of WM4 Magnet

Coil	A	B	C	Magnet
Inner Radius (mm)	19.0	56.0	115.0	19.0
Outer Radius (mm)	54.0	112.0	305.0	305.0
Height (mm)	153.1	283.2	503.8	
Conductor	CuAg	Cu	Cu	
Conductivity (%IACS)	75	98	98	
Current (A)	19700	19700	19700	19700
Field (T)	10.55	8.17	8.88	27.60
Power (MW	2.26	2.60	4.71	9.57
Number of Turns	45/16	65/28	113/88	
Thickniss of Turn (mm)	1.8905/ 3.7810	2.2458/ 4.4916	1.6396/ 3.2792	
Uniformity (ppm)				1180

"Water Cooled Resistive Magnet at CHMFL", to be published in IEEE on Applied Superconductivity 2016 June

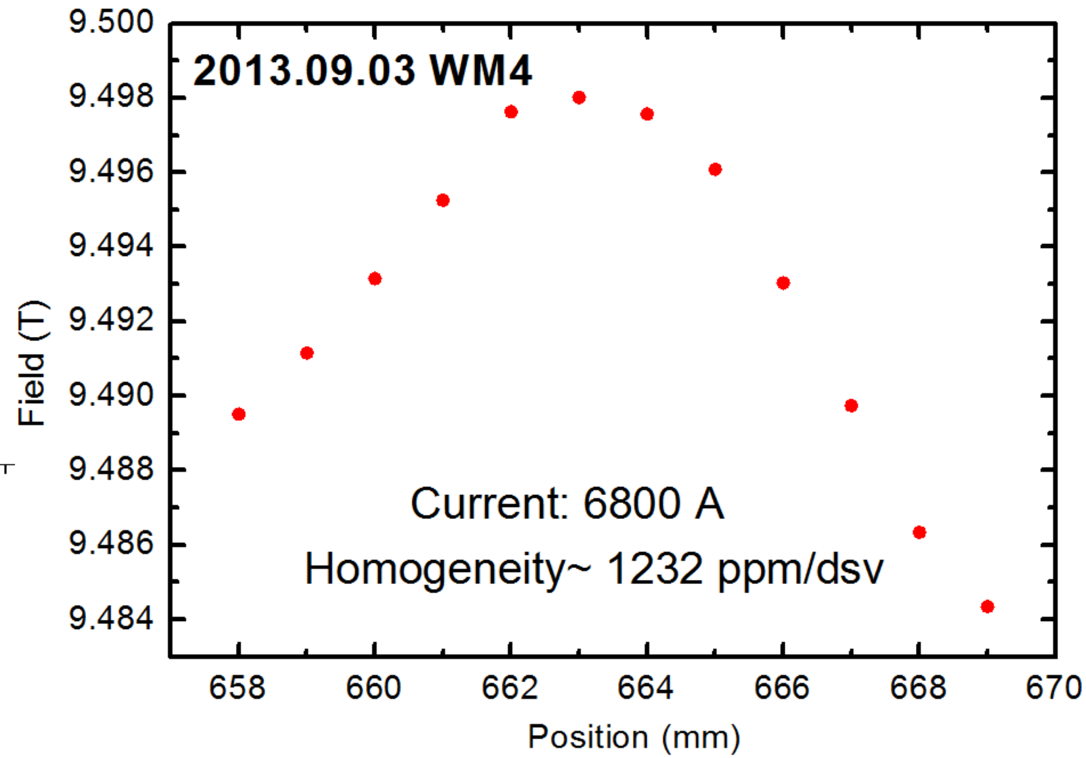
• WM4-C Coil Stacking

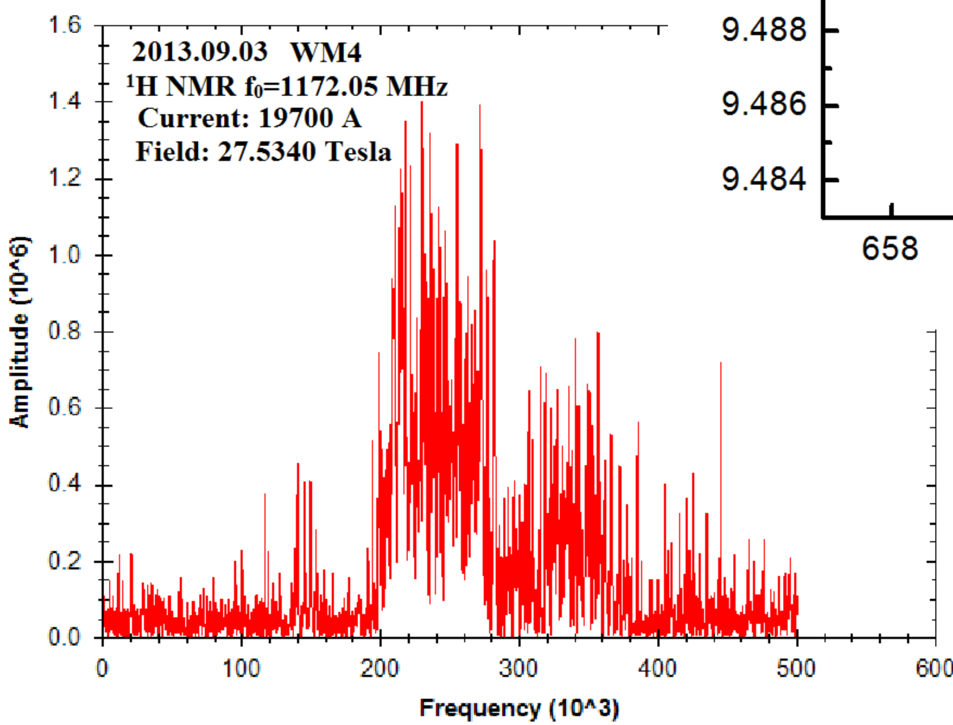
• Coils A,B,C of WM4 magnet



Calibration of the Magnetic Field by Nuclear Magnetic Resonance

WM4





27.534 T** / 19700 A

1232 ppm

2013-09-03

● WM2 Magnet, 50 mm bore

50 ppm,for MR

Bitter disks

Three Coils

Inner diameter

70 mm

Outer diameter

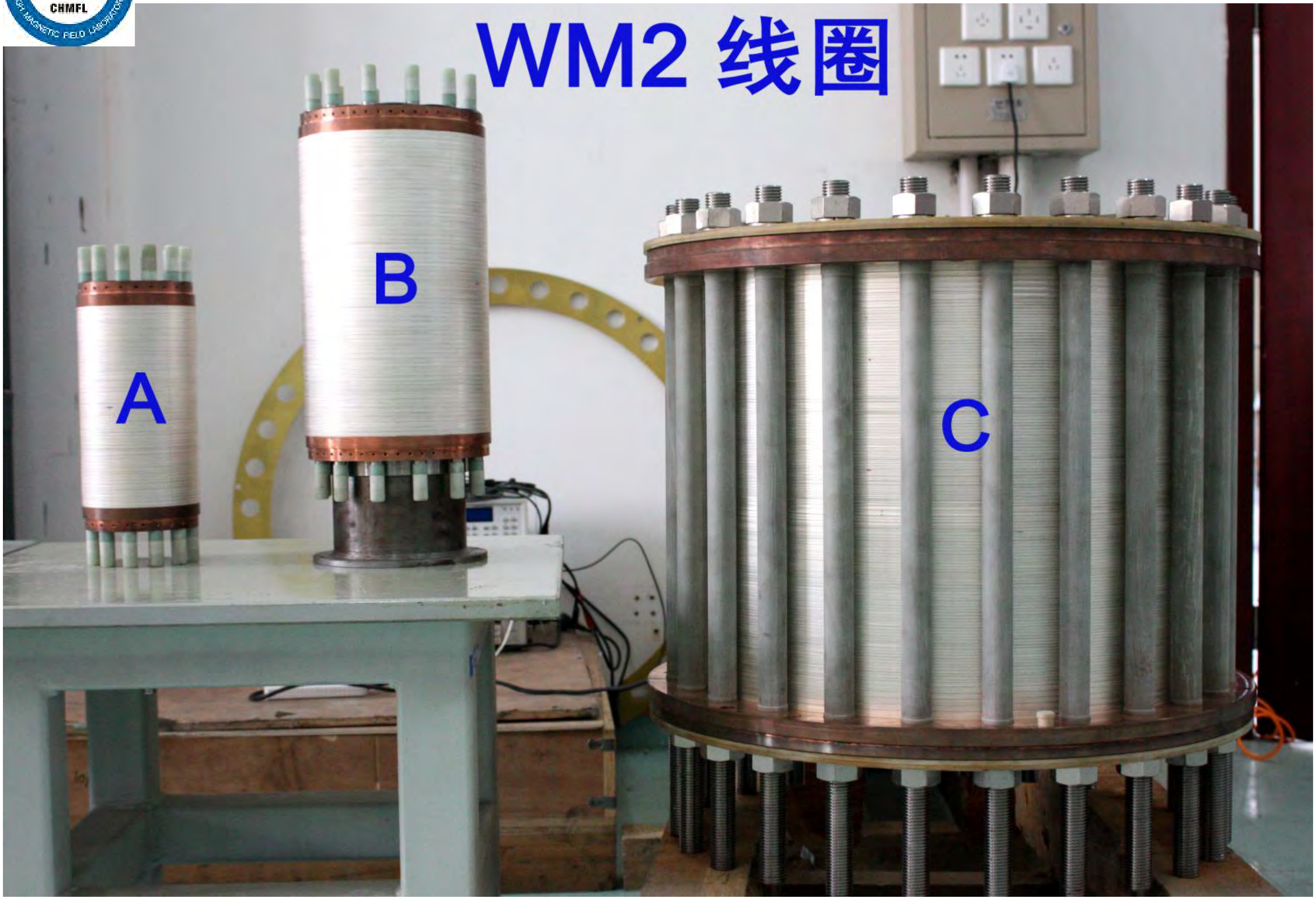
610 mm

● Parameters of WM2 Magnet

Coil	A	B	C	Magnet
Inner Radius (mm)	35.0	72.0	115.0	35.0
Outer Radius (mm)	70.0	112.0	305.0	305.0
Height (mm)	254.8	365.9	497.1	
Conductor	CuAg	Cu	Cu	
Conductivity (%IACS)	76.5	98	98	
Current (A)	32825	32825	32825	32825
Field (T)	8.91	6.76	9.33	25.0
Power (MW)	4.88	4.24	5.51	14.62
Number of Turns	14/48	67	124/12	
Thickniss of Turn (mm)	4.416/ 3.864	5.338	3.222/ 6.444	
Uniformity (ppm)				1.41

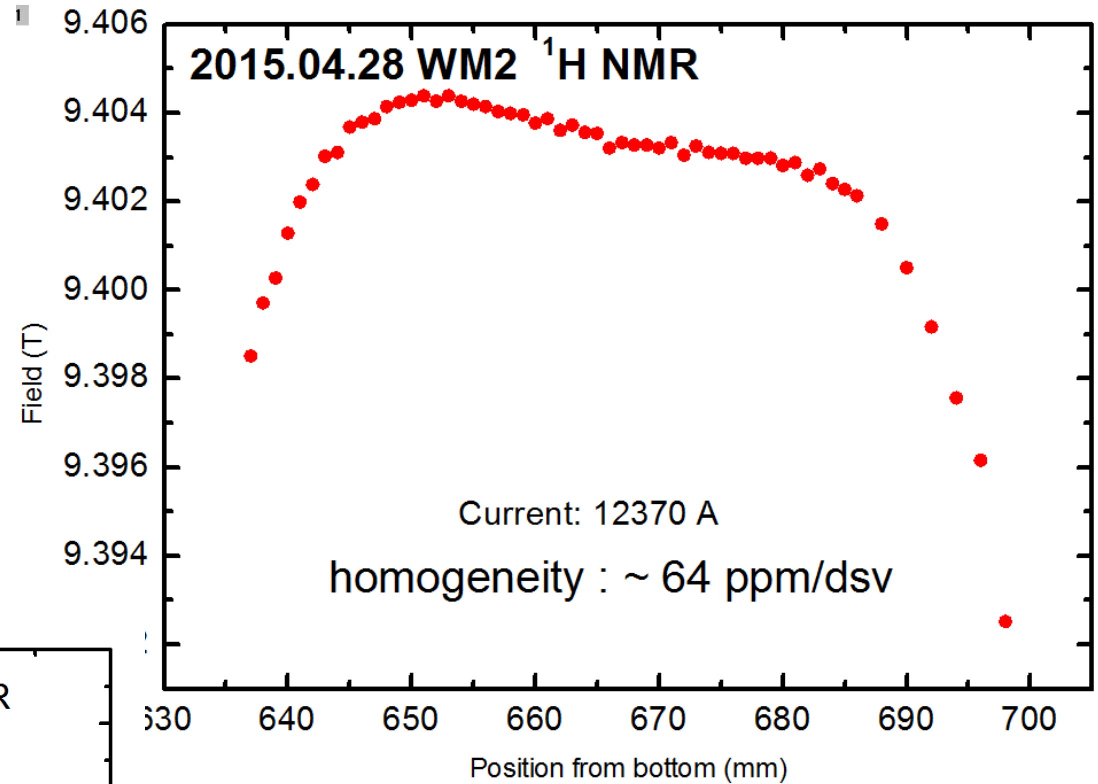
“Water Cooled Resistive Magnet at CHMFL”, to be published in IEEE on Applied Superconductivity 2016 June

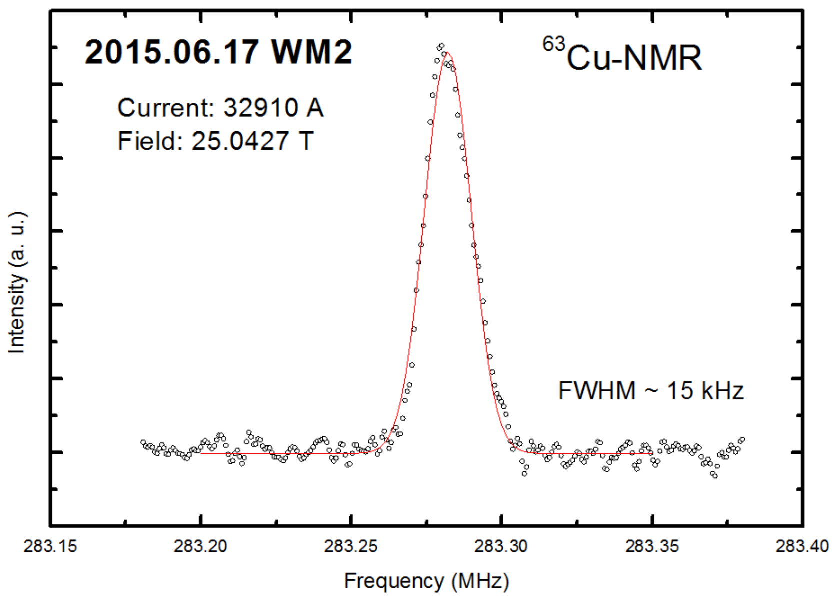
● Coils A,B,C of WM2 magnet



Calibration of the Magnetic Field by Nuclear Magnetic Resonance

WM2

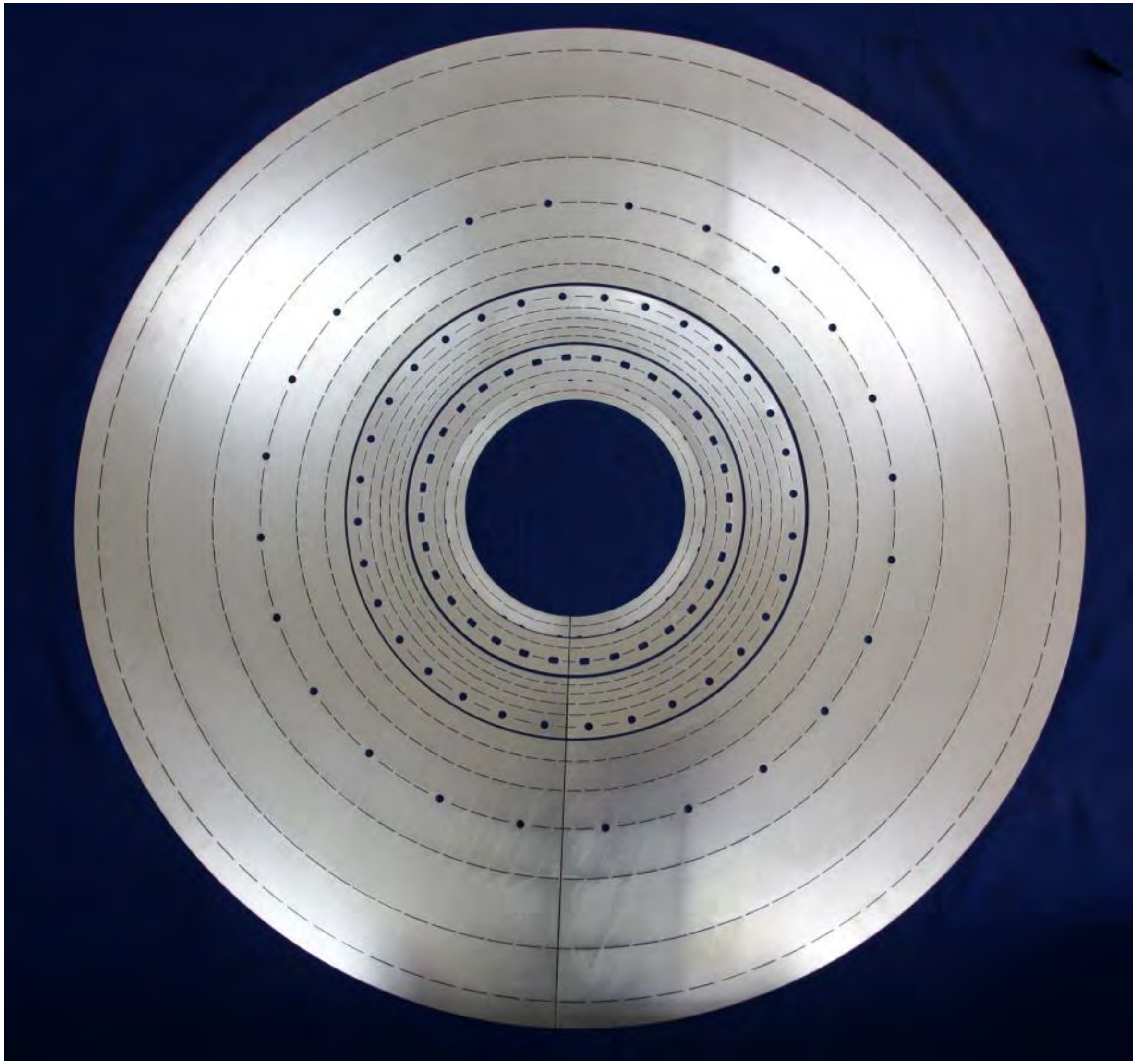




25.0427 T / 32910 A
2015-06-17

64 ppm
2015-04-28

(3) WM3 magnet, 200 mm bore



Bitter Disks

Four Coils

Inner diameter

200 mm

Outer diameter

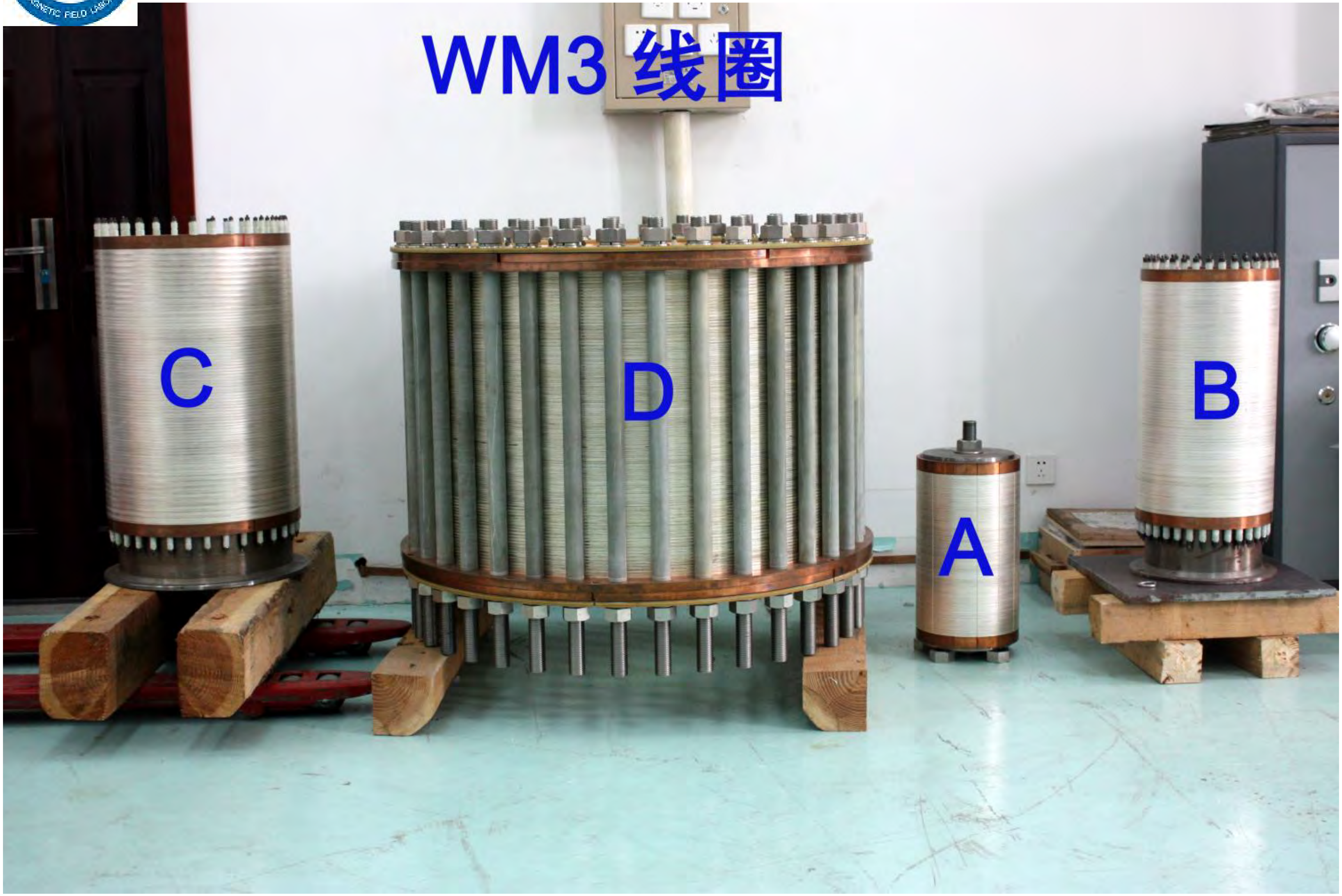
1000 mm

Parameters of WM3 Magnet

Coil	A1	A2	B	C	Magnet
Inner Radius (mm)	107.6	128.4	166.4	227.0	107.6
Outer Radius (mm)	127.6	163.4	224.0	500.0	500.0
Height (mm)	512.4	572.6	611.4	644.2	
Conductor	Cu	Cu	Cu	Cu	
Conductivity (%IACS)	98.	98.	98.	98.	
Current (A)	39650	39650	39650	39650	
Field (T)	2.49	3.71	5.43	8.34	19.94
Power (MW	1.52	2.76	5.94	8.94	19.16
Number of Turns	56/10/2	43/14/2	49/20	96/48	
Thickniss of Turn (mm)	6.000/ 12.000/ 24.000	6.808/ 13.616 27.232	6.774/ 13.549	3.262/ 6.524	
Uniformity (ppm)					177.

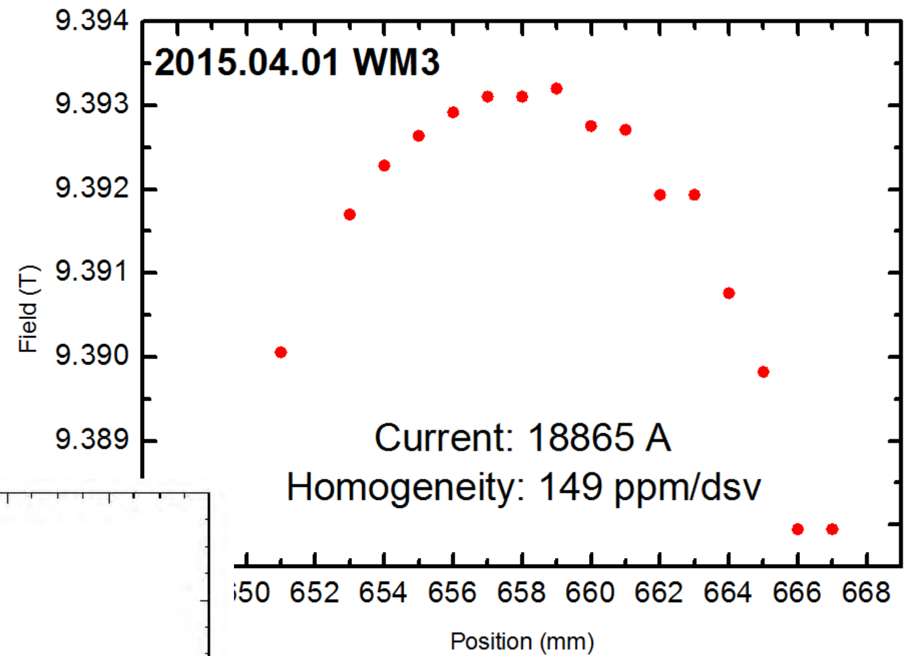
"Water Cooled Resistive Magnet at CHMFL", to be published in IEEE on Applied Superconductivity 2016 June

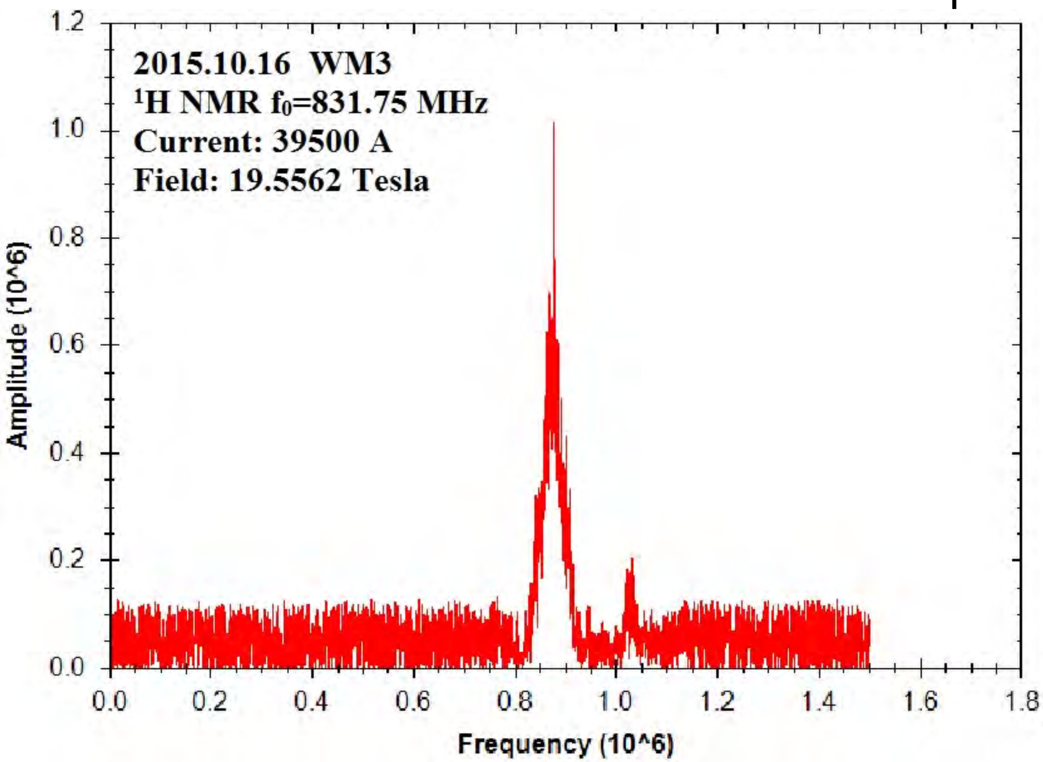
● Coils A,B,C,D of WM3 magnet



Calibration of the Magnetic Field by Nuclear Magnetic Resonance

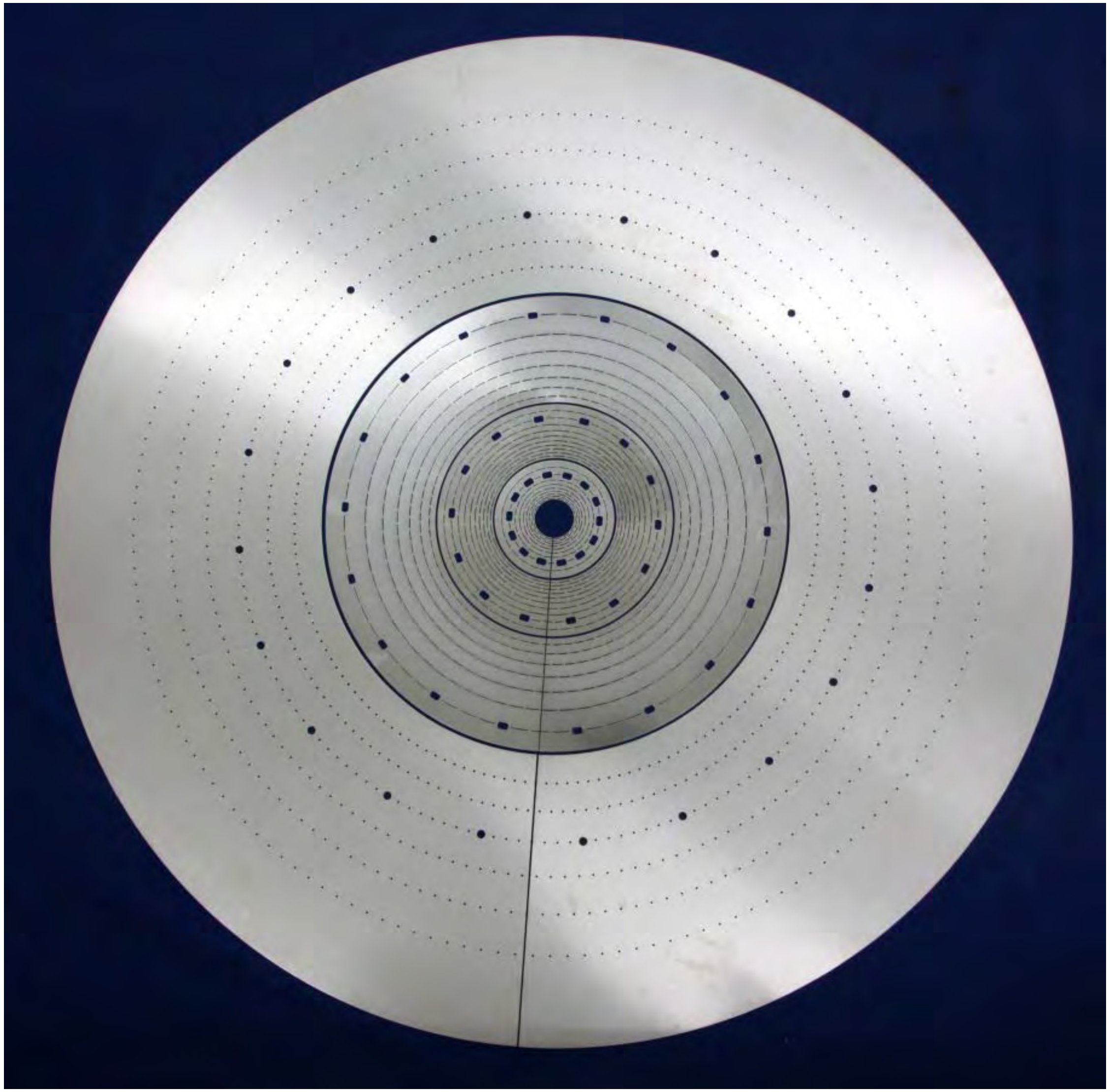
WM3





19.556 T / 39500 A
2015-10-16
149 ppm
2015-04-01

(3) WM1 / WM5 Magnets



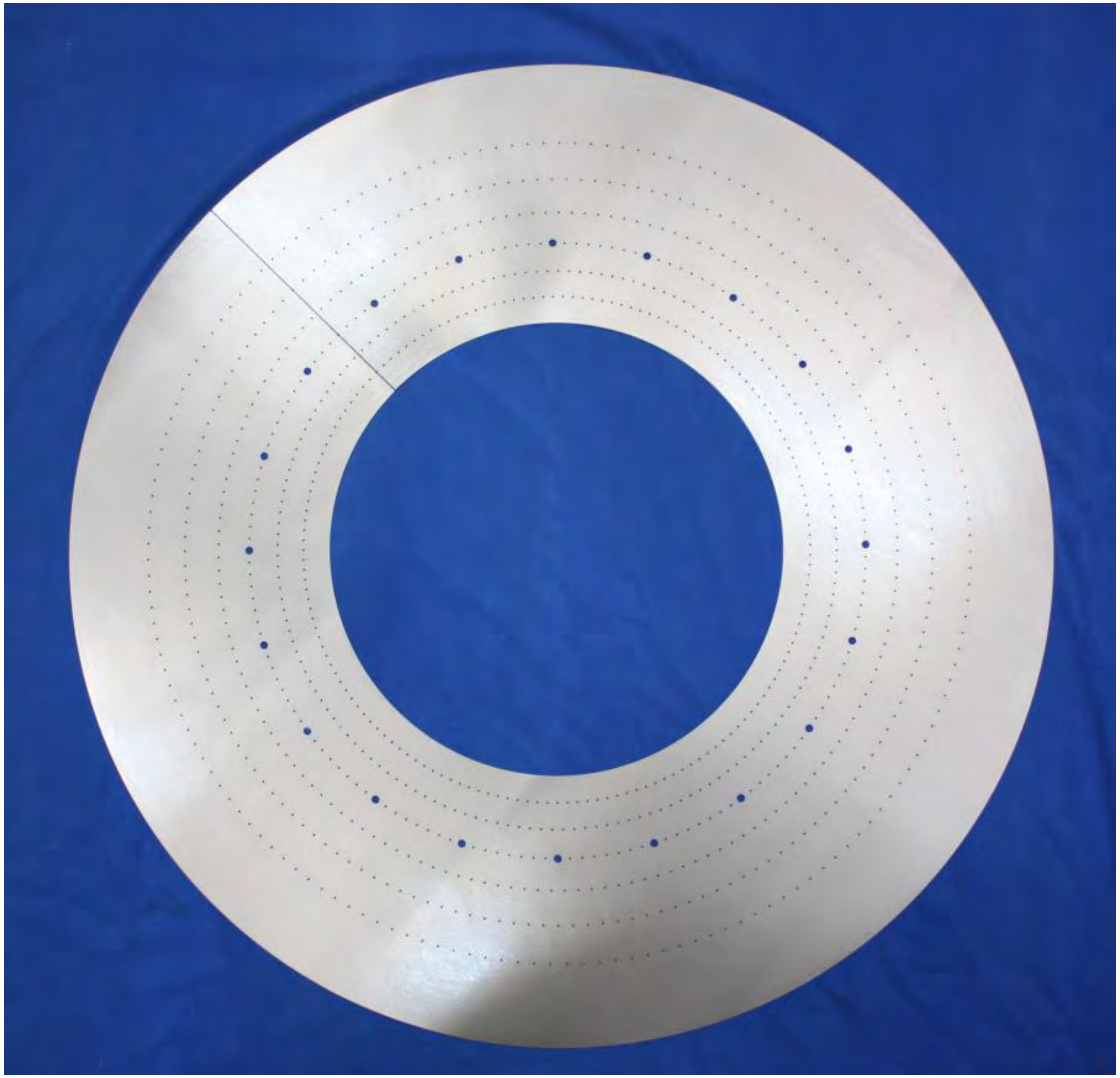
- **WM1 magnet**
  32 mm bore
  Bitter Disks
  Four Coils
  Inner diameter
  38 mm
  Outer diameter
  1000 mm

● Parameters of WM1 Magnet

Coil	A	B	C	D	Magnet
Inner Radius (mm)	19.0	60.0	114.0	227.0	19.0
Outer Radius (mm)	58.0	112.0	224.0	500.0	500.0
Height (mm)	249.3	371.4	550.5	653.5	
Conductor	CuAg	CuAg	Cu	Cu	
Conductivity (%IACS)	70.0	70.0	98.0	98.0	
Current (A)	37710	37710	37710	37710	37710
Field (T)	10.98	10.56	10.32	6.64	38.505
Power (MW)	2.69	8.32	8.44	5.63	25.08
Number of Turns	33/4/2/2	69/2/2/2	85/36	105/20	
Thickniss of Turn (mm)	3.7661/ 7.5322/ 15.0644/ 30.1288	1.0721/ 4.2886/ 8.5771/ 17.1542	3.411/ 6.822	4.4/8.8	
Uniformity (ppm)					467

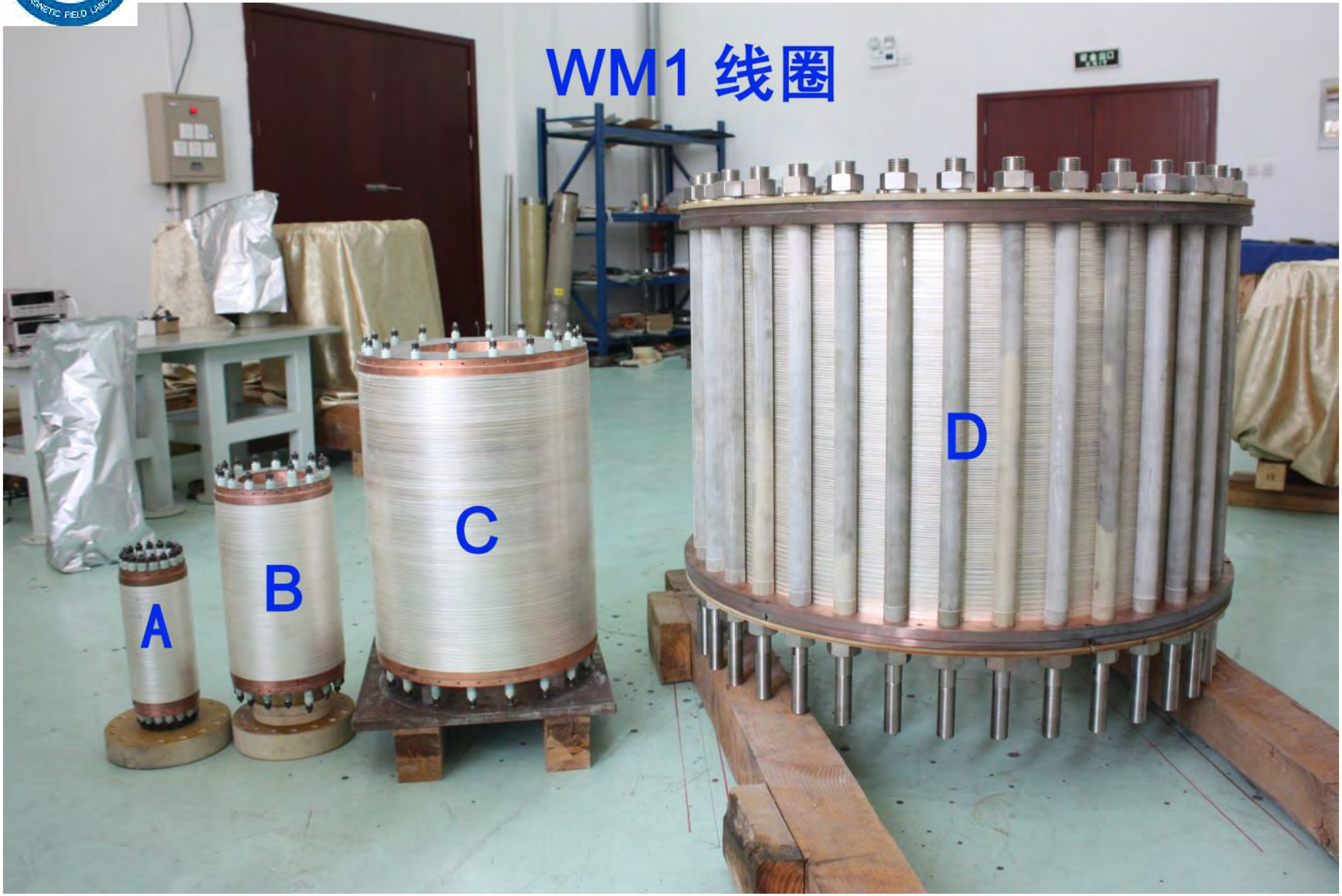
"Water Cooled Resistive Magnet at CHMFL", to be published in IEEE on Applied Superconductivity 2016 June

• Bitter Disk of WM1-D Coil



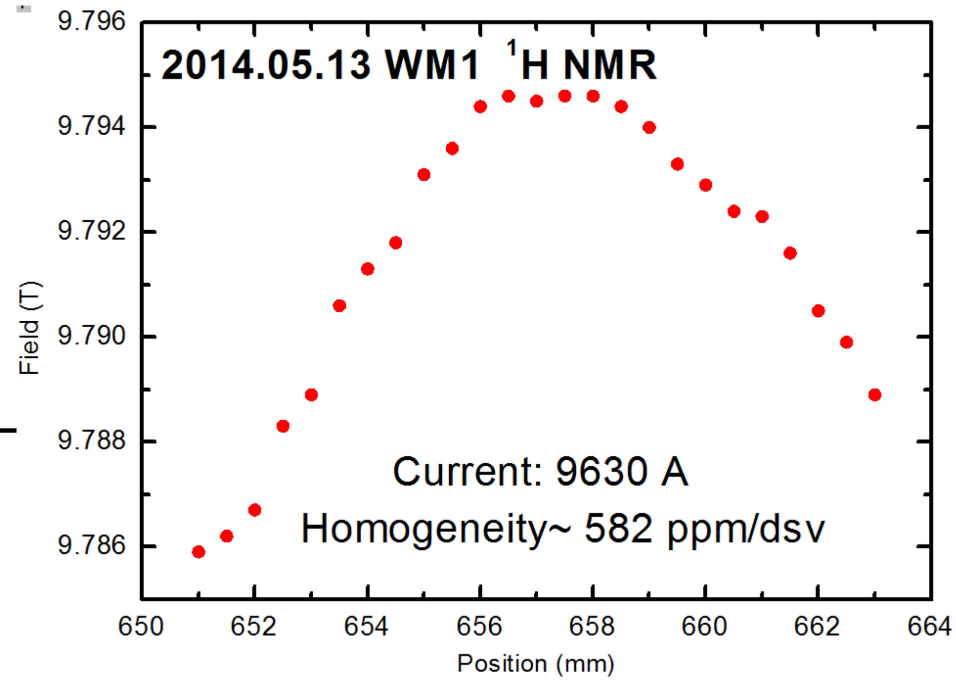
• Stacking of WM1-D coil

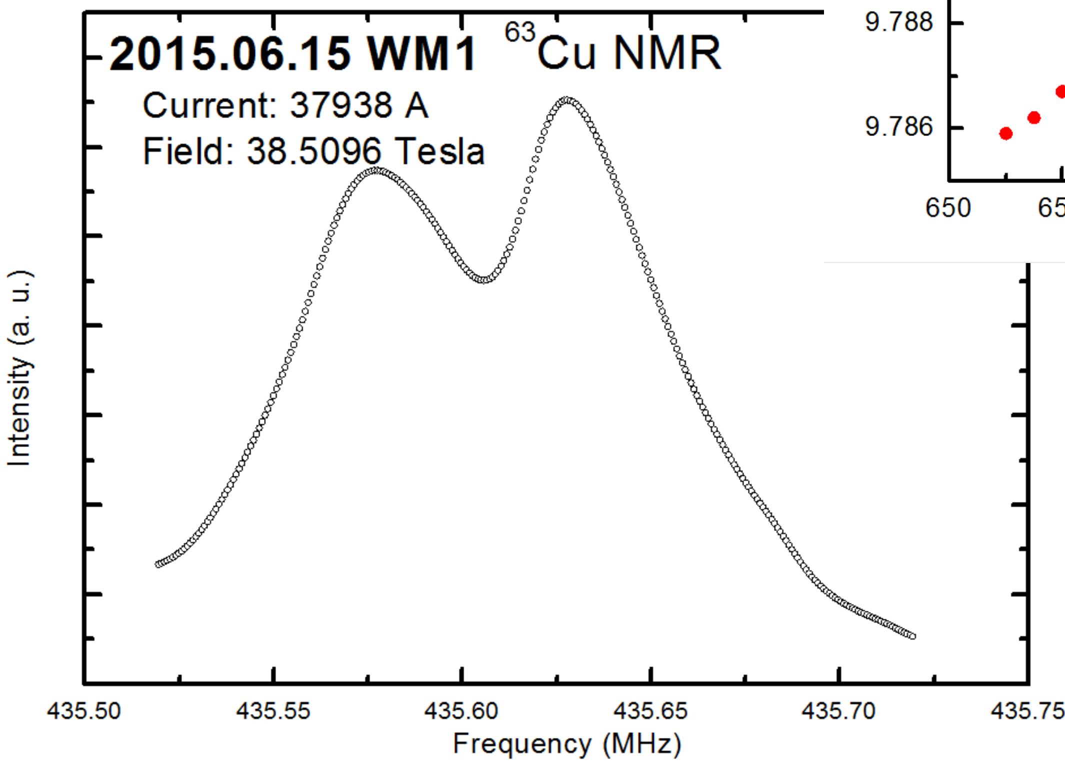
• Coils A,B,C,D of WM1 magnet



Calibration of the Magnetic Field by Nuclear Magnetic Resonance

WM1





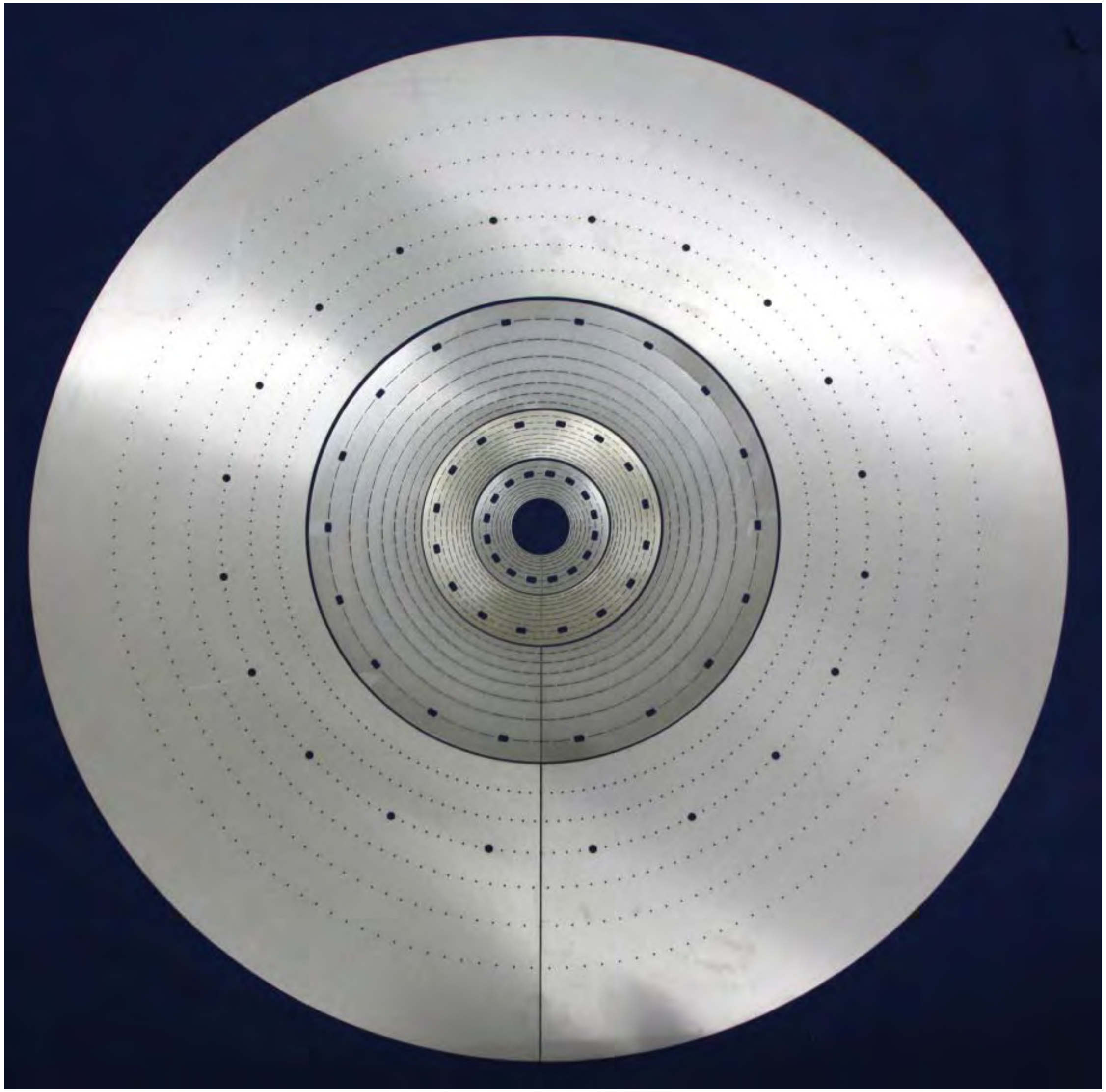
38.5096 T** / 37938 A

2015-06-15

582 ppm

2014-05-13

• WM5 Magnet, 50 mm bore



Bitter Disks

Four Coils

Inner diameter

56 mm

Outer diameter

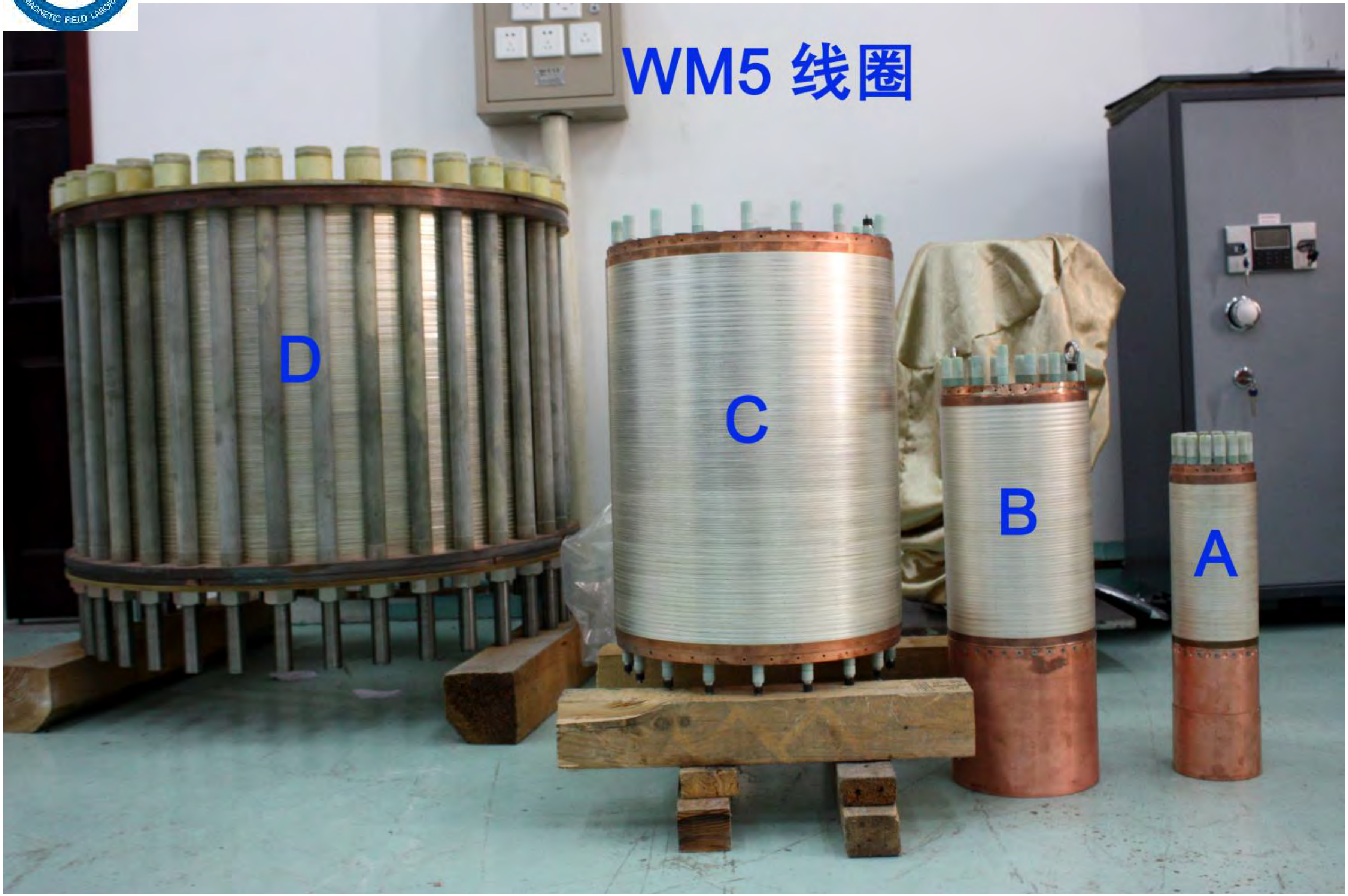
1000 mm

● Parameters of WM5 Magnet

Coil	A	B	C	D	Magnet
inner Radius (mm)	28.0	67.0	114.0	227.0	28.0
Outer Radius (mm)	65.0	112.0	224.0	500.0	500.0
Height (mm)	237.7	340.0	550.5	653.5	
Conductor	CuAg	CuAg	Cu	Cu	
Conductivity (%IACS)	70.0	70.0	98.0	98.0	
Current (A)	36820	36820	36820	36820	36820
Field (T)	9.52	8.97	10.08	6.49	35.052
Power (MW)	3.10	7.23	8.10	5.34	23.87
Number of Turns	35/6/2	60/2/2/2	85/36	105/20	
Thickniss of Turn (mm)	4.2255/ 8.4510/ 16.9020	4.2550/ 8.5101/ 12.7651/ 17.0202	3.411/ 6.822	4.4/8.8	
Uniformity (ppm)					415

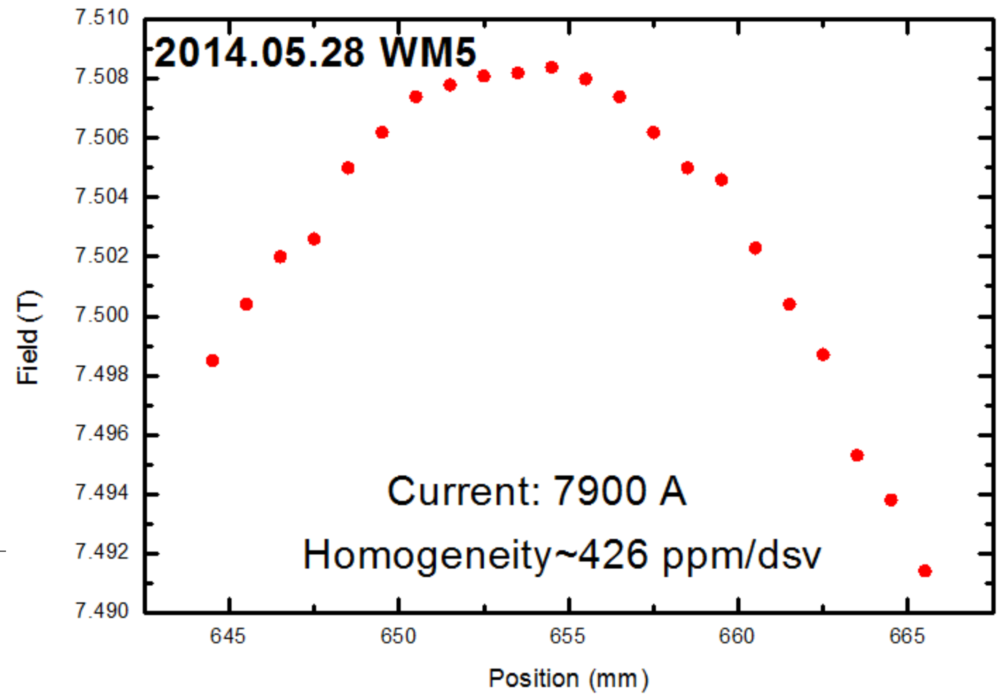
"Water Cooled Resistive Magnet at CHMFL", to be published in IEEE on Applied Superconductivity 2016 June

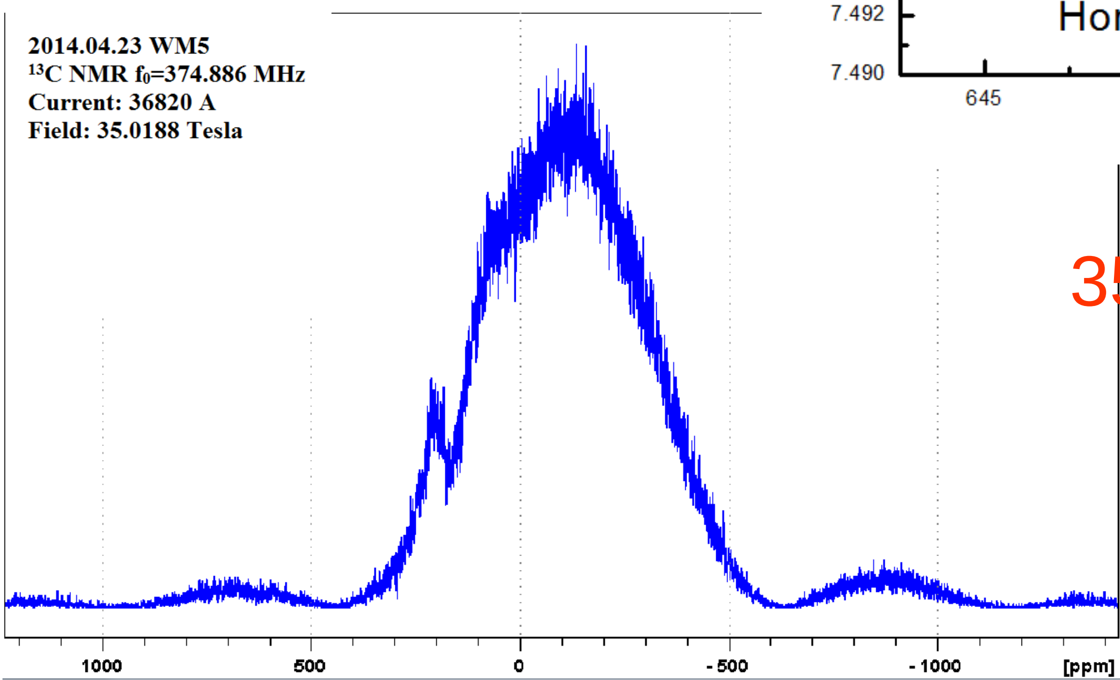
• Coils A,B,C,D of WM5 magnet



Calibration of the Magnetic Field by Nuclear Magnetic Resonance

WM5





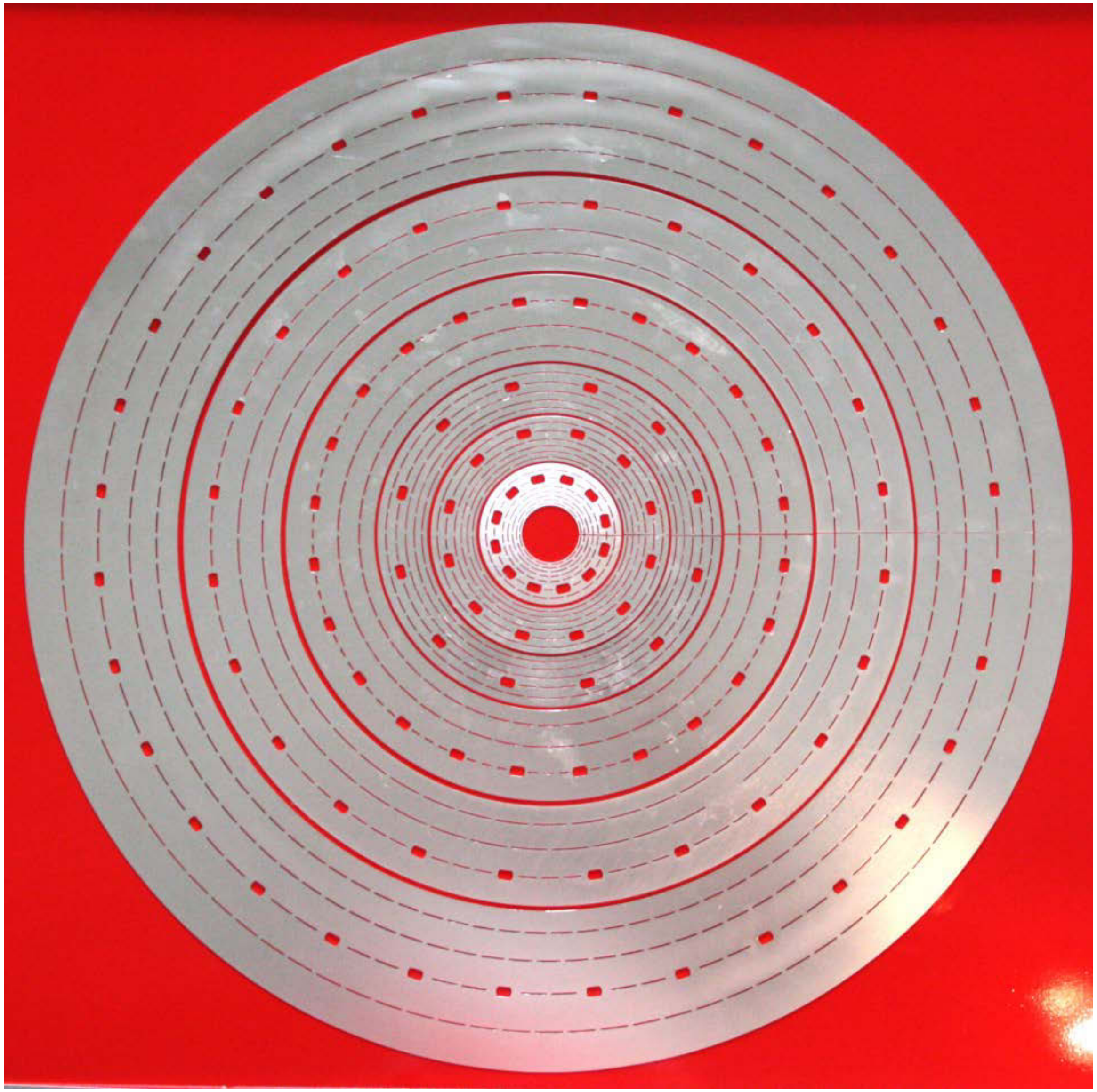
35.0188 T** / 36820 A

2014-04-23

426 ppm

2014-05-28

• Insert of Hybrid Magnet, HWM11



Bitter Disks

Six Coils

Inner diameter

38 mm

Outer diameter

710 mm

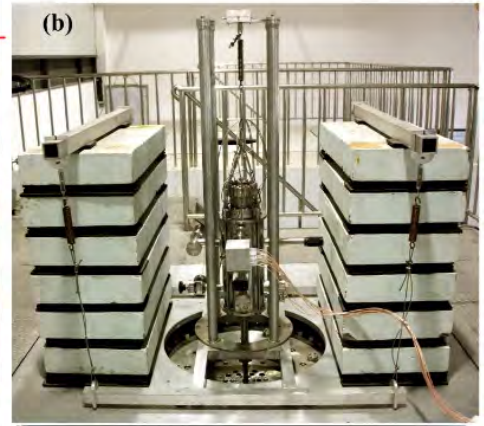
● Parameters of HWM11 Magnet

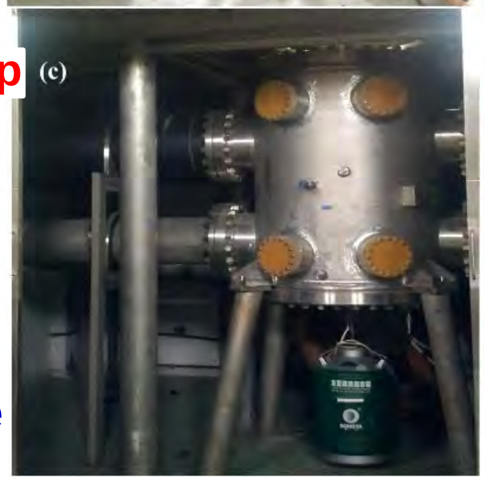
Coil	A	B	C	D	E	F	Magnet
Inner Radius (mm)	19.0	49.0	81.0	114.0	178.0	246.0	19.0
Outer Radius (mm)	47.0	79.0	112.0	175.0	243.0	350.0	350.0
Height (mm)	367.6	514.2	646.1	640.9	658.0	659.0	
Conductor	CuAg	CuAg	CuAg	Cu	Cu	Cu	
Conductivity (%IACS)	70.0	70.0	70.0	98.0	98.0	98.0	
Current (A)	38600	38600	38600	38600	38600	38600	
Field (T)	7.63	6.25	4.98	4.54	4.12	5.49	33.00
Power (MW)	2.24	4.09	4.74	2.70	3.64	7.92	25.35
Number of Turns	33/2/2/2	43/2/2/2	48/2/2	55/2/2	57/2/2	95/2	
Thickniss of Turn (mm)	5.962/ 11.924/ 23.848/ 47.696	7.154/ 14.309/ 28.618/ 57.235	8.883/ 17.766/ 35.532/ 53.298	9.457/ 18.914/ 37.828	9.427/ 18.854/ 37.709	6.282/ 25.126	
Uniformity (ppm)							127

"Water Cooled Resistive Magnet at CHMFL", to be published in IEEE on Applied Superconductivity 2016 June

• Coils A,B,C,D,E,F of insert of hybrid magnet

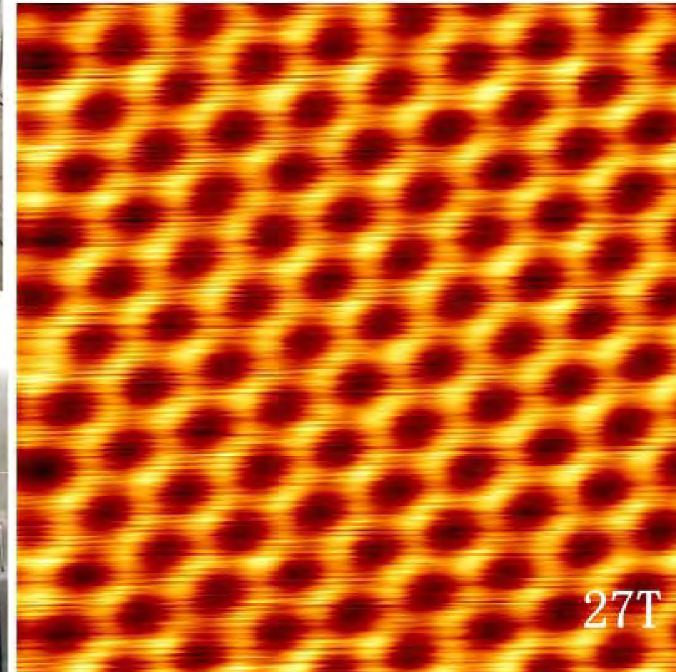
STM head driven by TunaDrive **(patent)**





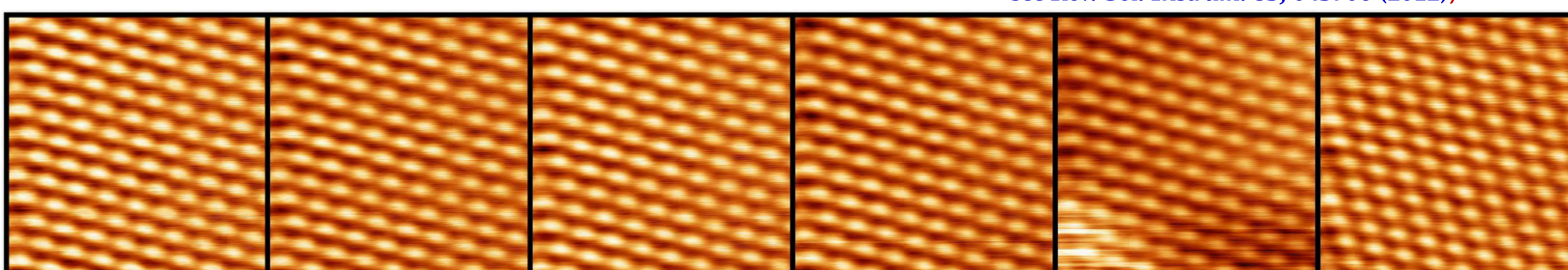
The first WM-STM !

[Published online by ***Nano Research*** (2015), DOI 10.1007/s12274-015-0889-5]



Graphite (raw data), 2 × 2 nm², 27 T.

(Previous record: 18T (in Superconducting magnet), see *Rev. Sci. Instrum.* 83, 043706 (2012))



27 T → 0 T

Continuous imaging in decreasing field

3. Summary

- All completed water cooled magnets of the CHMFL have been presented;
- High magnetic fields up to 38.5 T can be used for our users;
- A hybrid magnet will be completed and will be tested in the early next year;
- Now we are dedicated to improving the experimental conditions for users;
- We have been accumulating experience in resistive magnet operation and protection.

4. Perspective-1

- Water cooled resistive magnets still the only way to generate the highest continuous magnetic fields;
- It combines with outer superconducting magnet to generate higher fields;.
- We should generate the fields of both magnets, water cooled resistive magnet and outer super-conducting magnet of hybrid magnet, as high as possible;

4. Perspective-2

- **Next targets of higher field for water cooled resistive magnets could be:**

1) 41-42 T with 28 MW;
2) 46 T with 42 MW, may be more;
3) 50 T with 56 MW, may be more.

- **The corresponding fields for hybrid magnets would be:**

1) 46 - 48 T;
2) 55 T;
3) 60 T.

5. Acknowledgment

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I want to thank my colleagues and their contribution on power supply, water cooling and control system.

I also want to thank Dr. Schneider-Muntau for interesting discussions.