# R&D Progress of the High Field Magnet Technology for CEPC-SPPC

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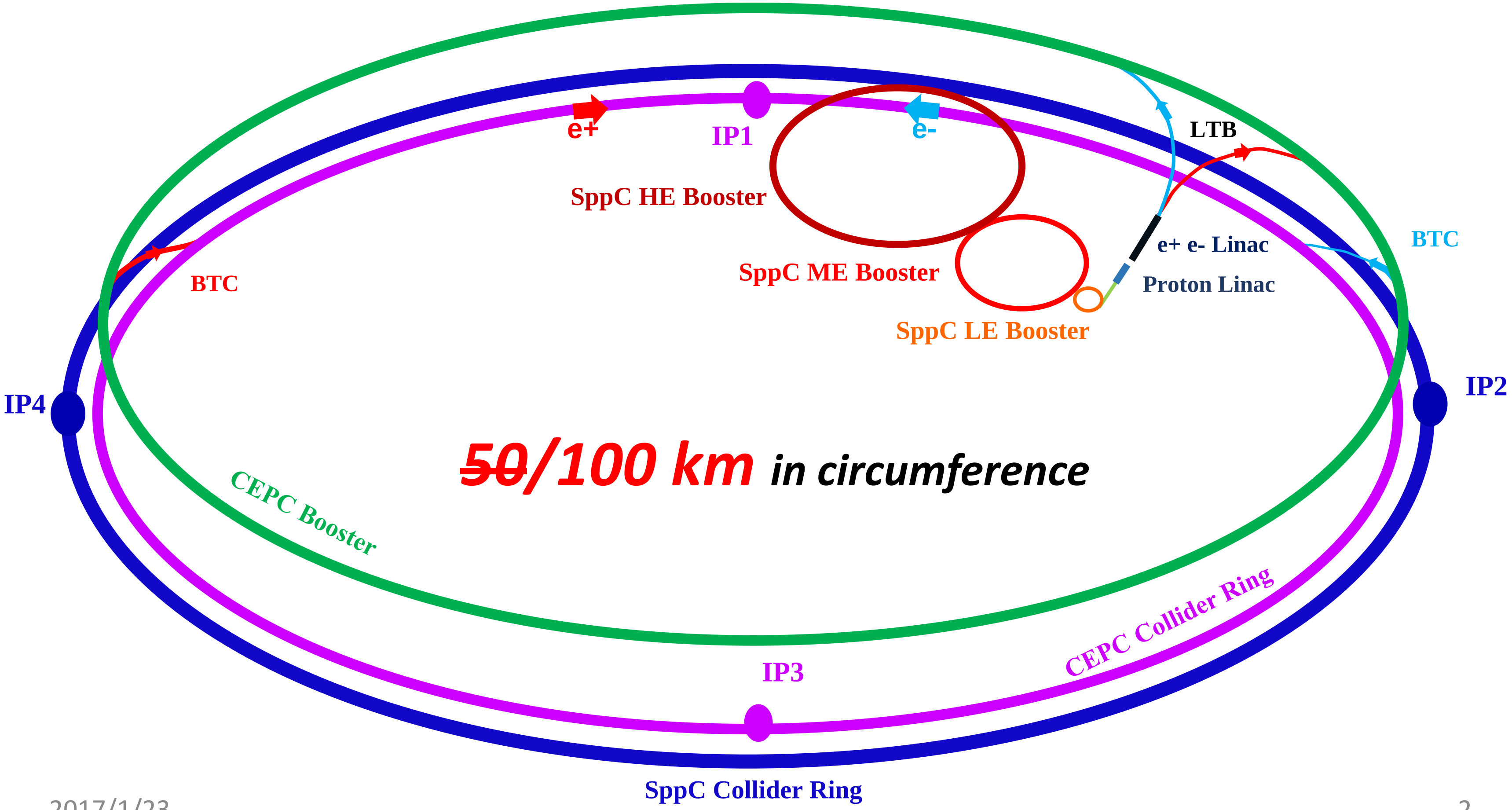
HKUST，Jan. 19th, 2017

# CEPC-SPPC

**CEPC** is an 240-250 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider **SPPC**, to study the new physics beyond the Standard Model.



~~50~~/100 km in circumference

# Specifications of the SPPC Magnets

**SPPC**

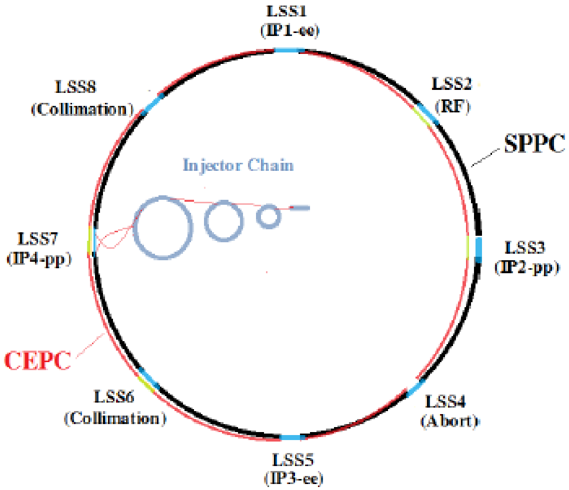
- *50/**100** km in circumference*
- *C.M. energy 70 TeV or higher*
- *Timeline*

*Pre-study: 2013-2020*
*R&D: 2020-2030*
*Eng. Design: 2030-2035*
***Construction: 2035-2042***

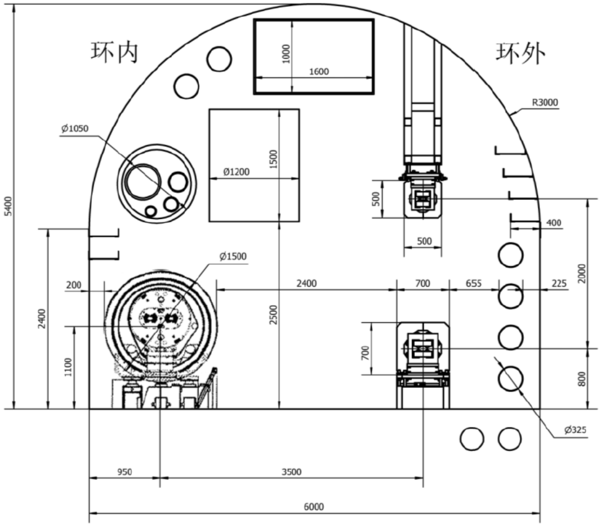
***Main dipoles*** $E[GeV] = 0.3 \times B[T] \times \rho[m]$

- *Field strength: 20~12 Tesla ?*
- *Aperture diameter: 40~50 mm*
- *Field quality: $10^{-4}$ at the 2/3 aperture radius*
- *Outer diameter: 900 mm in a 1.5 m cryostat*
- *Tunnel cross section: 6 m wide and 5.4 m high*

The CEPC-SPPC ring sited in Qinhuangdao, 50 km and 100 km options .



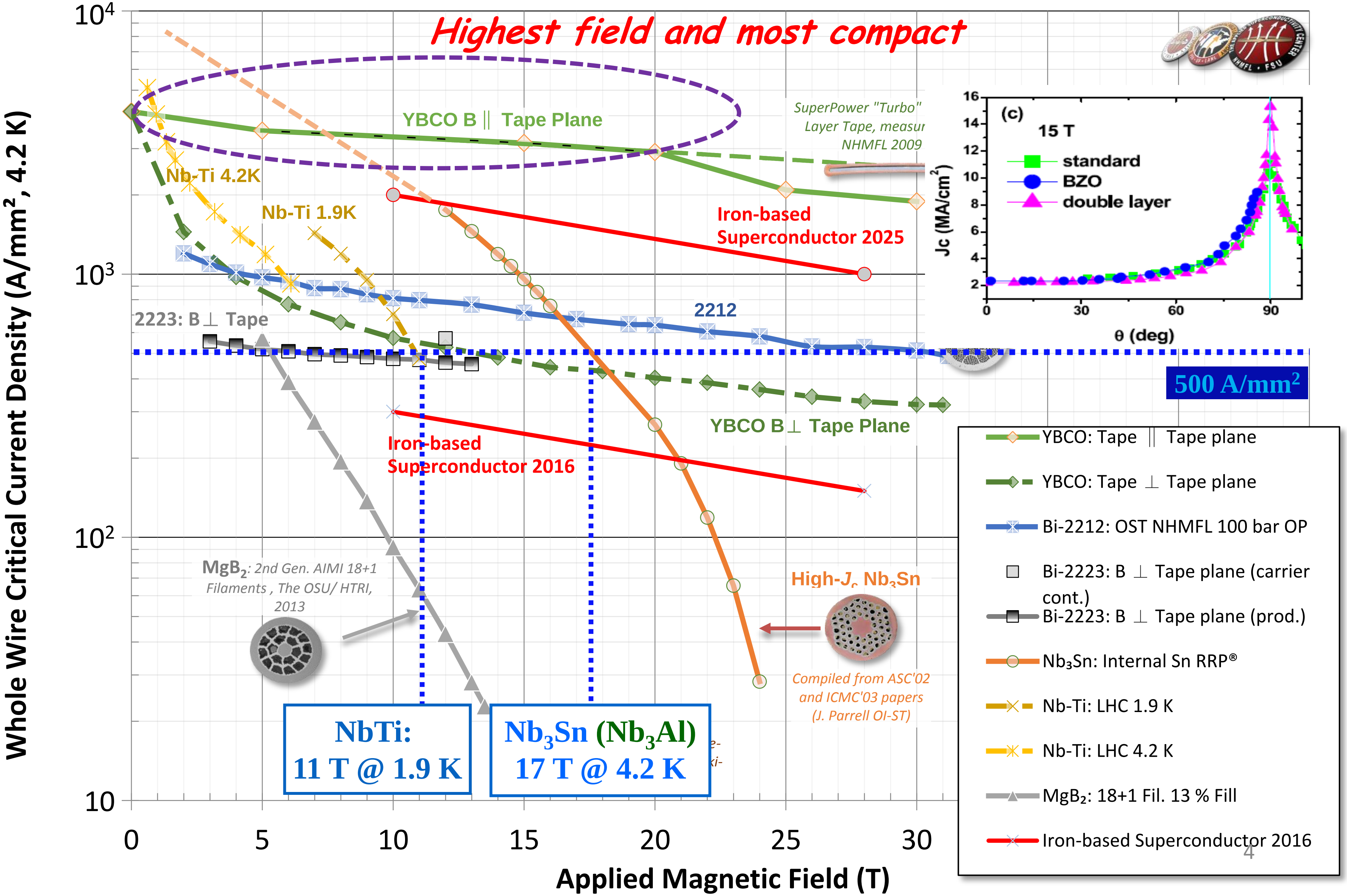
SPPC accelerator complex



6-m Tunnel for CEPC-SPPC. Left: SPPC collider. Right: CEPC collider (bottom) and Booster (top)

*Refer to CEPC-SPPC Pre-CDR, Mar. 2015: [http://cepc.ihep.ac.cn/preCDR/volume.html](http://cepc.ihep.ac.cn/preCDR/volume.html)*

# How to design a “good” accelerator magnet?



*Highest field and most compact*

500 A/mm²

**NbTi:**
**11 T @ 1.9 K**

**$Nb_3Sn$ ($Nb_3Al$)**
**17 T @ 4.2 K**

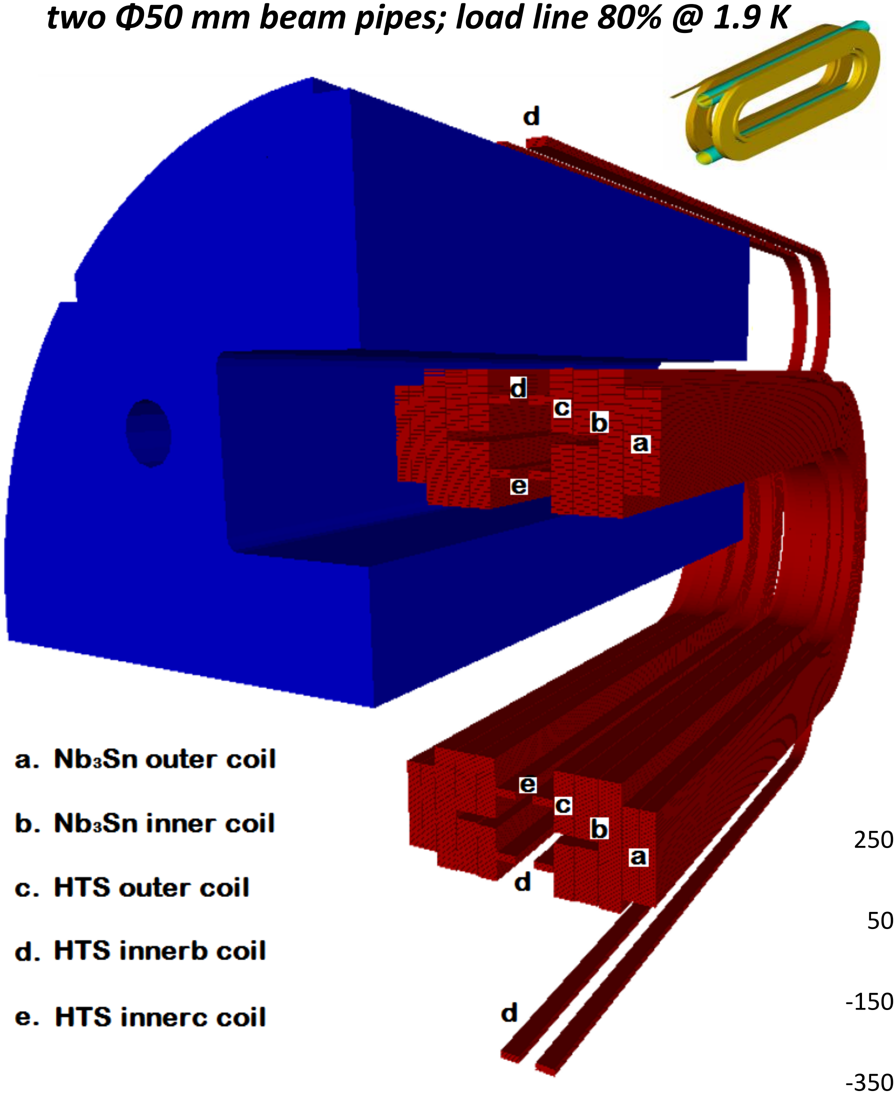
# Concept of the SPPC 20-T Dipole Magnet

*Q. Xu et al.*

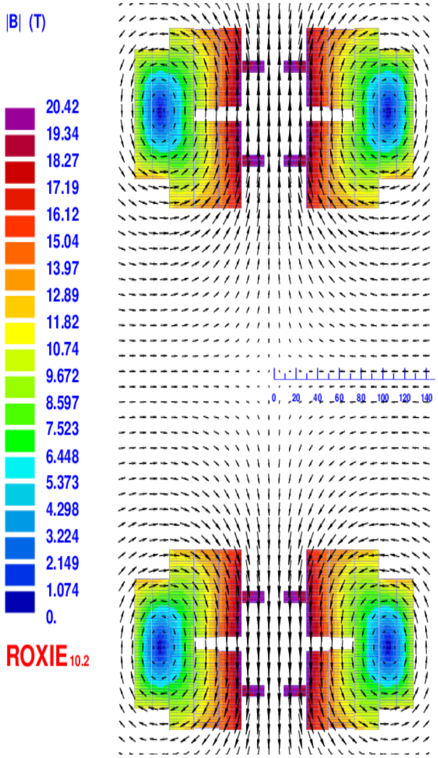
## *With common coil configuration*

*20-T dipole magnet with common coil configuration*

*two Φ50 mm beam pipes; load line 80% @ 1.9 K*

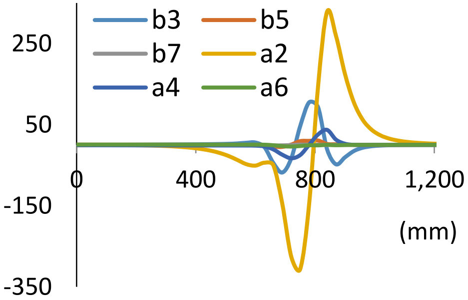


- **a. Nb₃Sn outer coil**
- **b. Nb₃Sn inner coil**
- **c. HTS outer coil**
- **d. HTS innerb coil**
- **e. HTS innerc coil**



### *Main parameters of the magnet*

| | |
|---|---|
| Number of apertures | 2 |
| Aperture diameter (mm) | 50 |
| Inter-aperture spacing (mm) | 333 |
| Operating current (A) | 14700 |
| Operating temperature (K) | 4.2 |
| Operating field (T) | 20 |
| Peak field (T) | 20.4 |
| Margin along the load line (%) | 11 |
| Stored magnetic energy (MJ/m) | 7.8 |
| Inductance (mH/m) | 72.1 |
| Yoke ID (mm) | 260 |
| Yoke OD (mm) | 800 |
| Weight per unit length (kg/m) | 3200 |
| Energy density (coil volume) (MJ/m$^3$) | 738 |
| Force per aperture – X / Y (MN/m) | 23.5/4.4 |
| Peak stress in coil (MPa) | 240 |
| Fringe Field @ r = 750 mm (T) | 0.02 |



### *Integrated field quality*

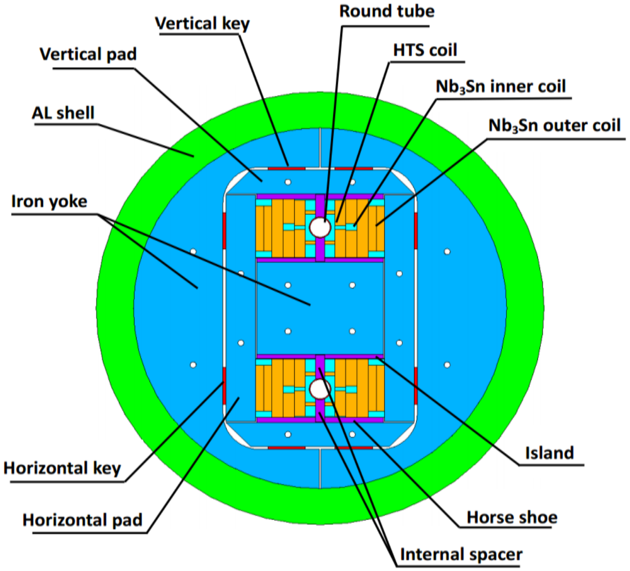
| Integrated $b_n$ & $a_n$ | Value ($10^{-4}$) |
|---|---|
| b3 | 0.14 |
| b5 | 1.42 |
| b7 | -0.40 |
| a2 | -0.29 |
| a4 | -1.81 |
| a6 | 0.03 |

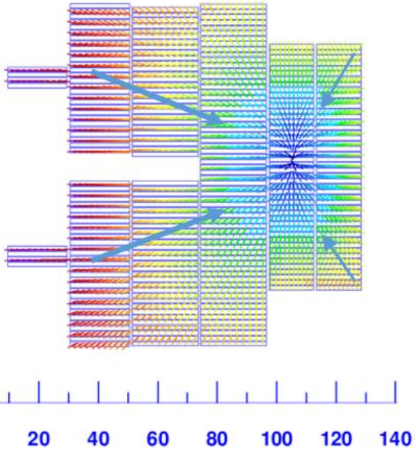
*Q. Xu et. al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016，4000404*

# Concept of the SPPC 20-T Dipole Magnet

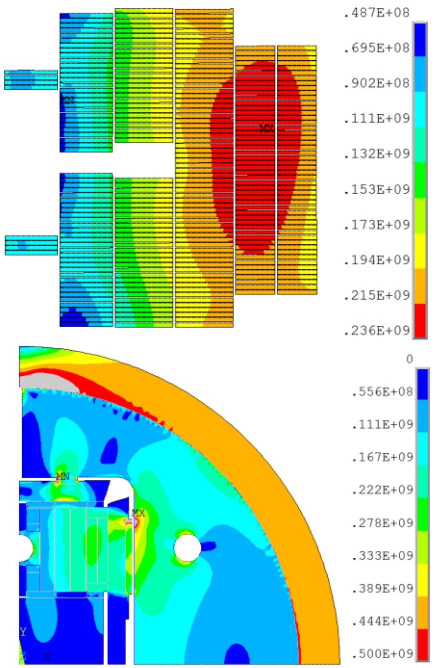
*K. Zhang, Q. Xu et al.*

*With common coil configuration*



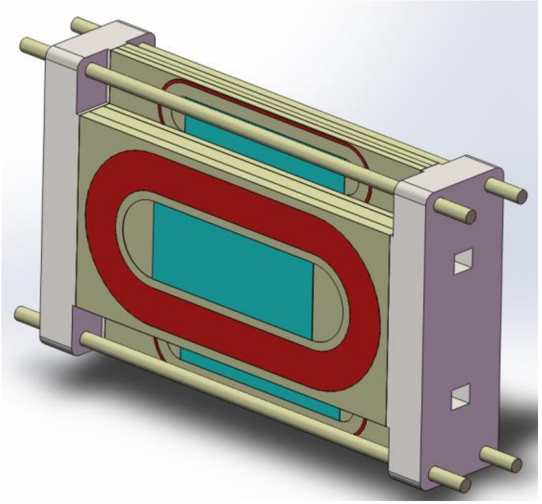


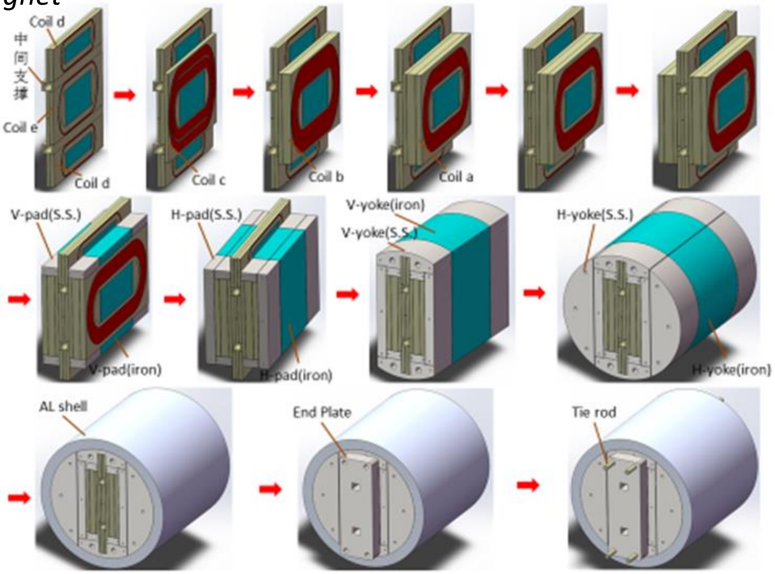
**Lorentz force per aperture:**
**Fx=23.4 MN/m ; Fy=2.38 MN/m**

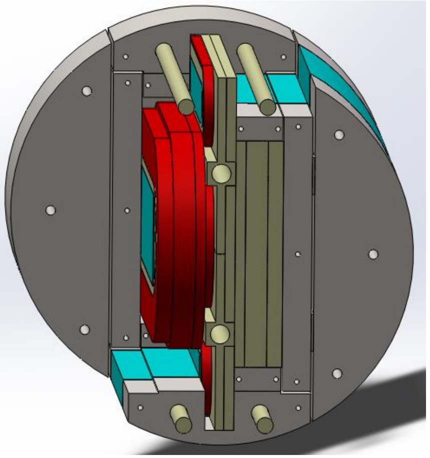


*Stress distribution after excitation*

*2D & 3D structure of the 20T dipole magnet*







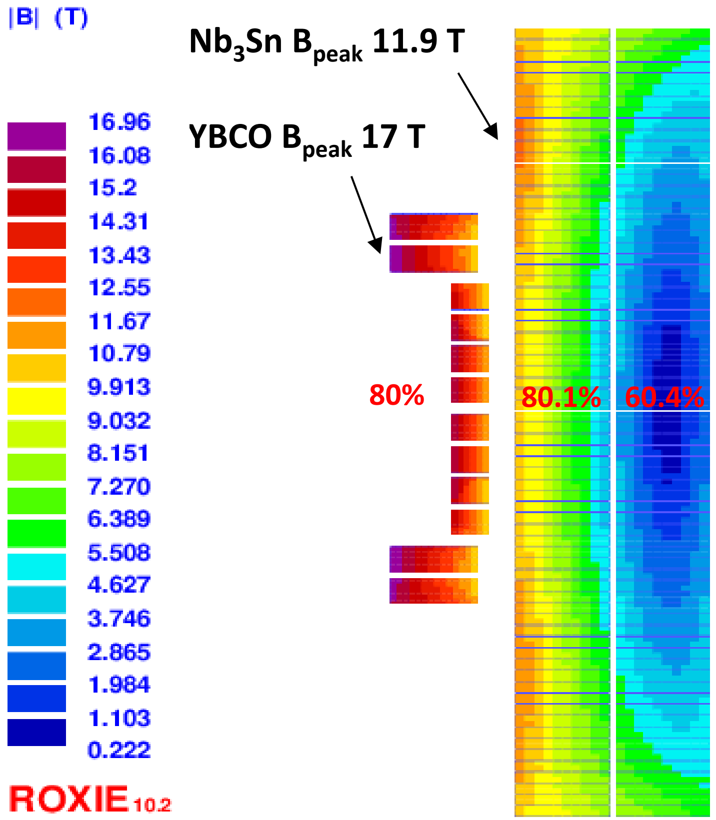
K. Zhang et. al., 2-D Mechanical Design Study of a 20-T Two-in-One Common-Coil Dipole Magnet for High-Energy Accelerators, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016, 4003705

# Concept of the SPPC 16T Dipole Magnet

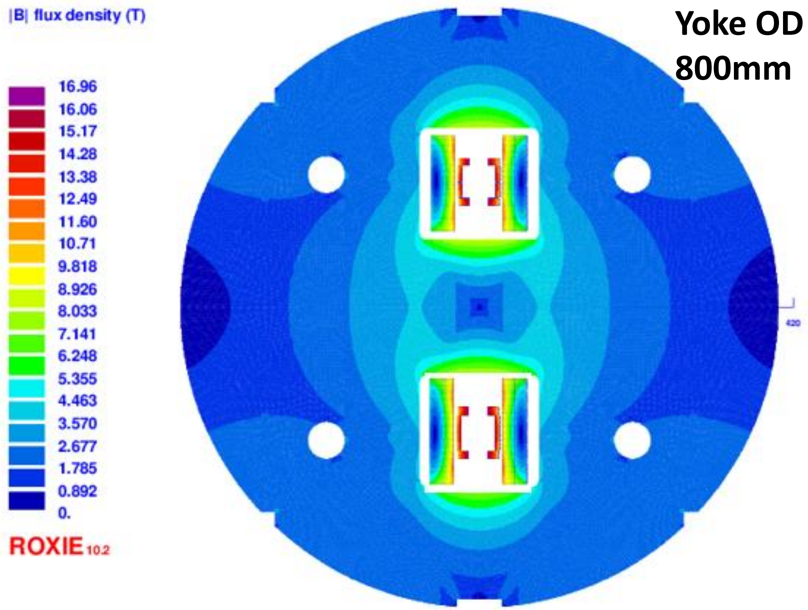
*C. Wang, Q. Xu et al.*

## *With Combined Common-coil and Block-type configuration*

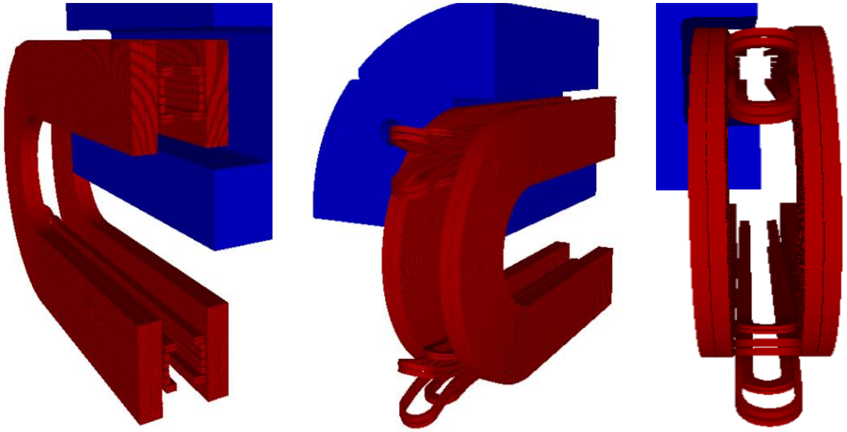
*16-T dipole magnet with two Φ45 mm beam pipes and the load line of 80% @ 4.2K*



**Field distribution in coils with an operating current of 0.8kA in ReBCO and 12kA in $Nb_3Sn$ in the 1st quadrant. $Nb_3Sn$ provides 11.2 T and ReBCO provides 4.8 T.**



Field distribution in the straight section of the magnet



Different perspectives of coil layout in the ends

# All-HTS 20T magnet?

- **Precondition (Iron based conductor, ReBCO, Bi-2212)**

➢ The Je of the HTS conductors is high enough for accelerator application

➢ The cost is lower than or similar with the LTS conductors

➢ Mechanical performance is qualified

- **Main challenges of the HTS technology**

➢ Field quality control： $10^{-4}$ field uniformity needed for accelerators

➢ Quench protection： quench propagation speed of HTS conductors is about two orders of magnitude lower than the LTS case

➢ Cable fabrication： how to fabricate high-current cable with tapes?

➢ Coil layout： compact, high efficiency, stress control, …

- **Advantages of the all-HTS magnet：**

➢ Possibility of reducing the cost significantly (Iron based conductor, ReBCO)

➢ Possibility of raising the operation temperature of the magnet（4.2K -> ?K）

# 20T vs. 16T

- **To realize the 20T or 16T magnets and be capable of mass production, we need**
  - Significantly further reduce the cost of superconductors ($Nb_3Sn$ and HTS), i.e., to 1/5 or 1/10 of the present price
  - Qualify the HTS conductors in mechanical performance, field quality control, quench protection, and cables and coils should be easy to fabricate
- **Difficulty /Time needed for R&D /Grant needed for R&D**
  - 16T all $Nb_3Sn$ or $Nb_3Sn$+HTS： /normal 5~10 years /~10M RMB per year
  - 16T all HTS： /very difficult 10~20 years /~30M RMB per year
  - 20T $Nb_3Sn$+HTS： /difficult 10~15 years /~20M RMB per year
  - 20T all HTS： /very difficult 15~20 years />30M RMB per year
- **Cost**
  - $Nb_3Sn$+HTS： cost of 16T magnet is about 50% of the 20T magnet
  - All HTS： cost of 16T magnet is about 70% of the 20T magnet

# SPPC Design Scope (201701 version)

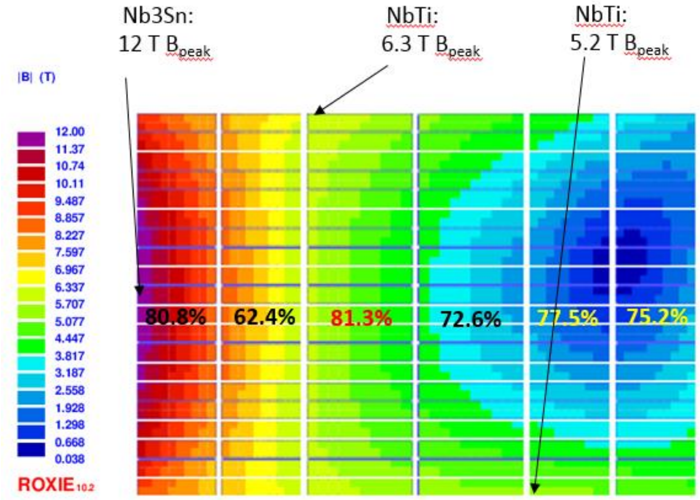
*Y. Wang, J. Tang, Q. Xu et al.*

- **Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, using iron-based HTS technology
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV
- **Upgrading phase**
  - Dipole magnet field: 20 -24T, iron-based HTS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)
- **Development of high-field superconducting magnet technology**
  - Starting to develop required HTS magnet technology before applicable iron-based HTS wire is available (in 5~10 years)
  - models by ReBCO (or Bi-2212) and LTS wires can be used for specific studies: stress management, quench protection, field quality control and fabrication methods

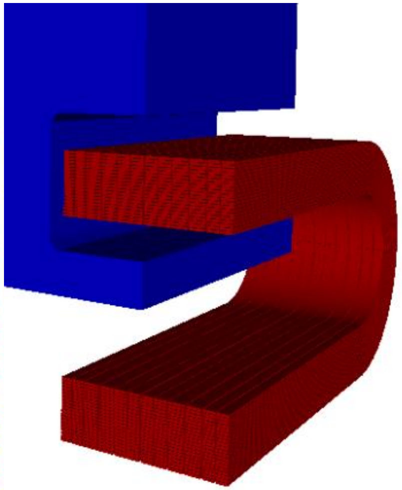
# High Field Magnet R&D 2016-2018

## Development of a 12T NbTi+$Nb_3Sn$ subscale magnet (~mid of 2017)

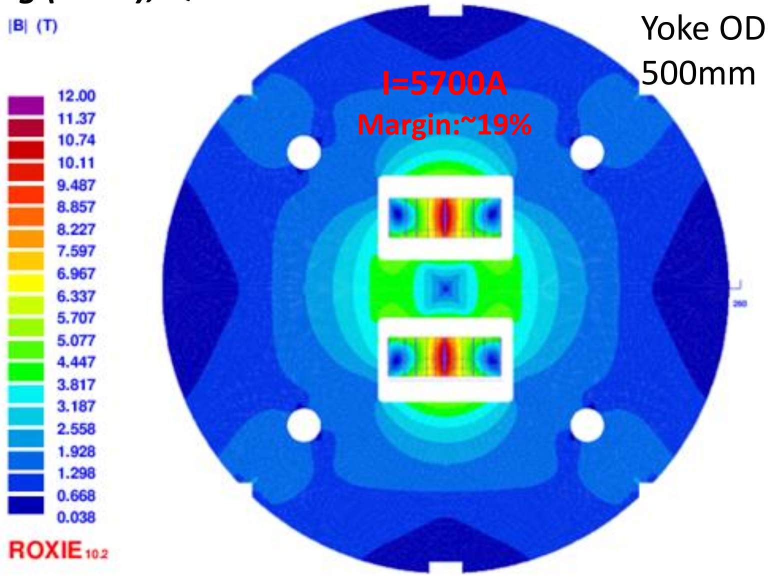
*C. Wang, K. Zhang, Y. Wang, D. Cheng, E. Kong (USTC), Q. Xu et al.*



Field distribution in the straight section

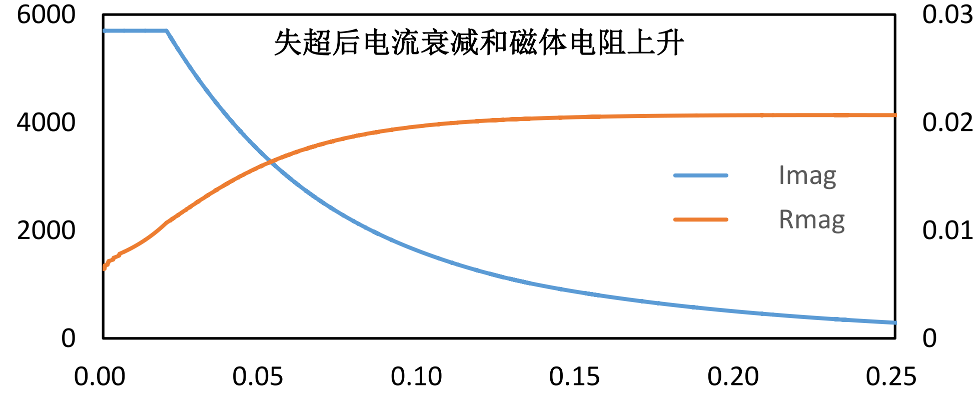


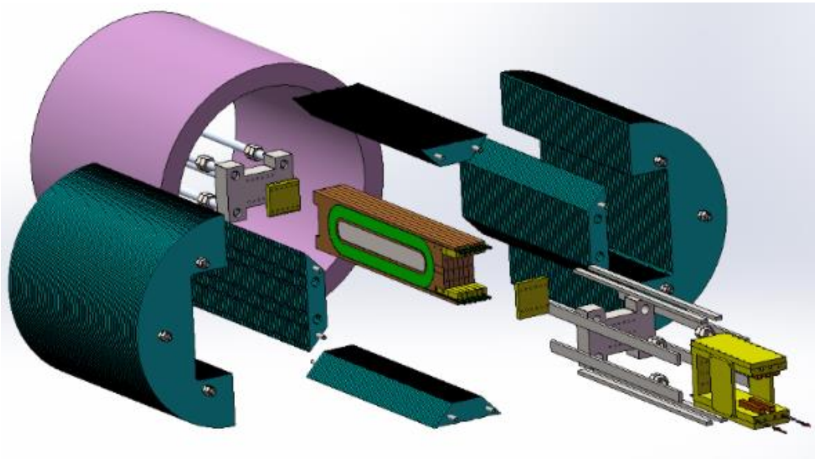
**3d coil layout**



Yoke OD
500mm

| 运行电流 | 泄能电阻 | 最高温度 | 对地电压 | MIITs | 磁体电阻 |
|---|---|---|---|---|---|
| 5700A | 80mΩ | 69K | 454V | 1.65 | 20.7mΩ |



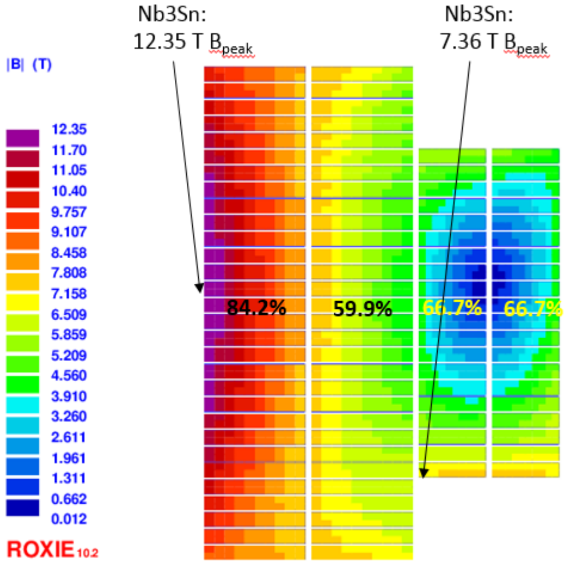


**Components and assembly**

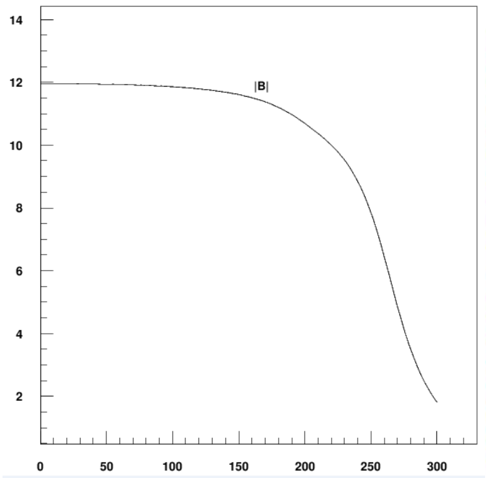
# High Field Magnet R&D 2016-2018

## Development of a 12T Nb$_3$Sn twin-aperture magnet (~Dec. 2017)

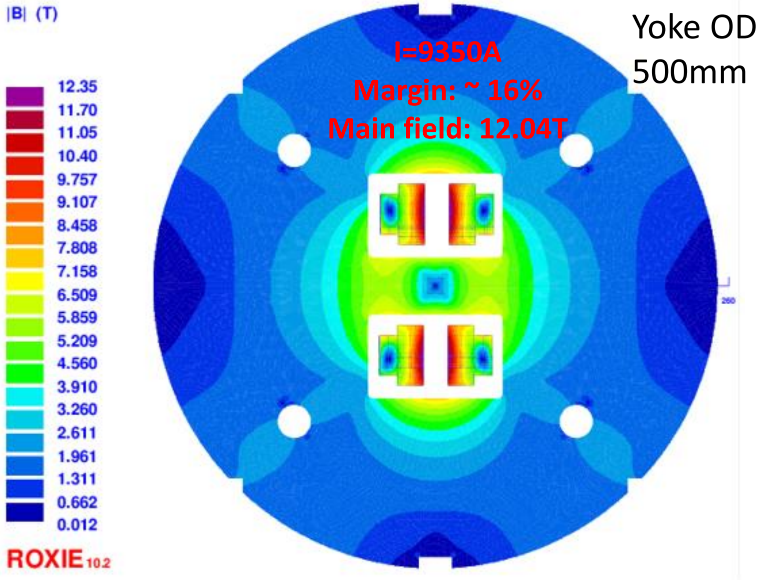
*K. Zhang, C. Wang, Y. Wang, D. Cheng, E. Kong (USTC), Q. Xu et al.*



Field distribution in the straight section



Field distribution along the Z-axis with the straight length of 400mm

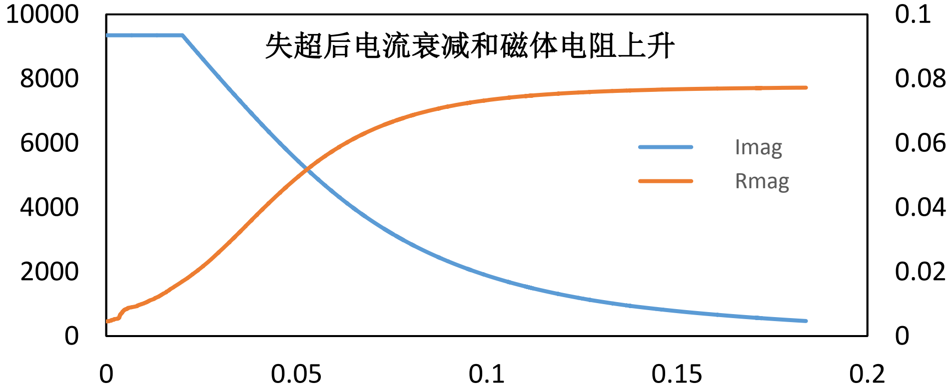


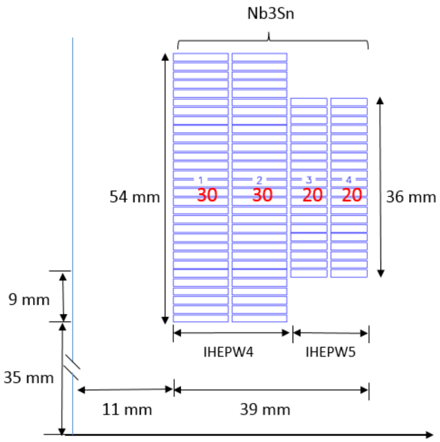
Yoke OD 500mm

**Clear bore diameter 22 mm**

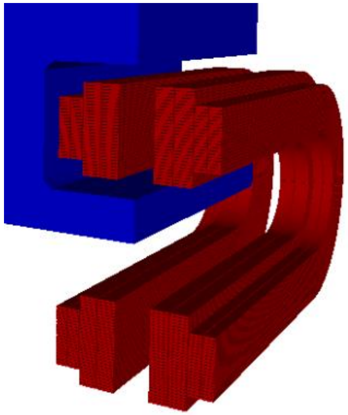
**Inter-aperture spacing 124 mm**

| 运行电流 | 泄能电阻 | 最高温度 | 对地电压 | MIITs | 磁体电阻 |
|---|---|---|---|---|---|
| 9350A | 50mΩ | 191K | 465V | 4.12 | 77.2mΩ |





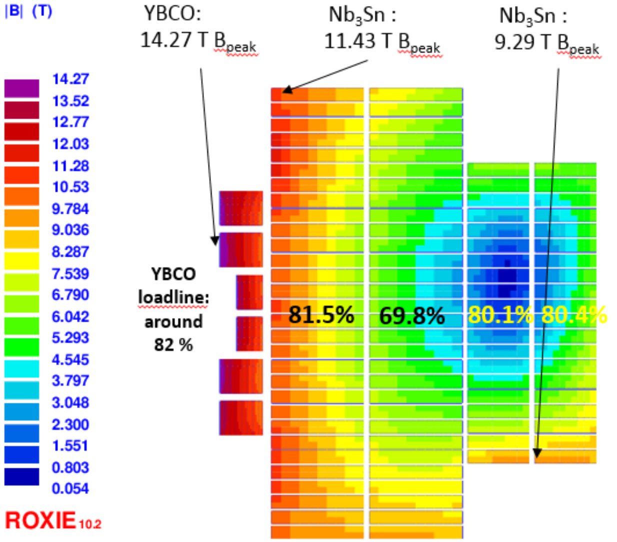
**3d coil layout**



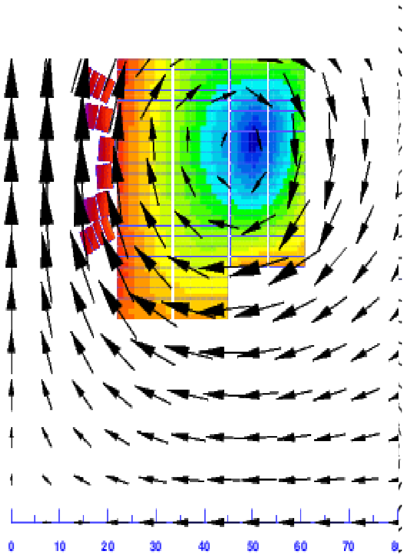
# High Field Magnet R&D 2016-2018

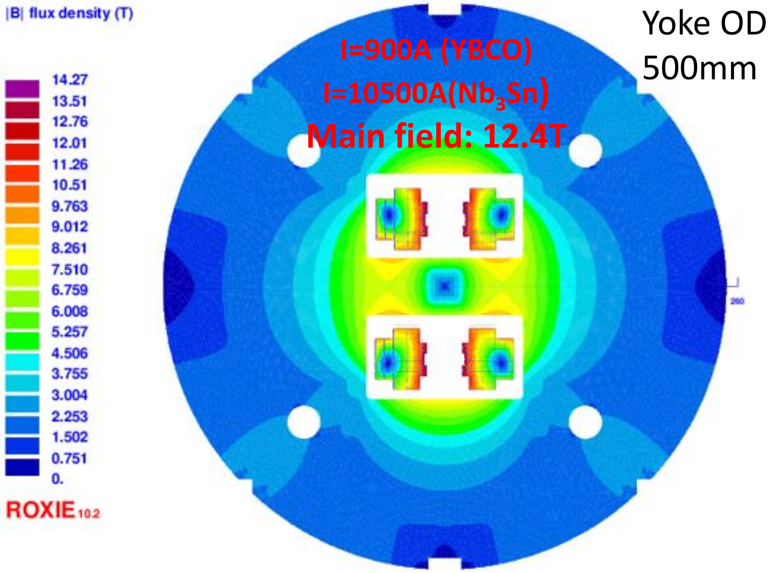
## Development of a 12T $Nb_3Sn$+HTS twin-aperture magnet (~Dec. 2018)

*K. Zhang, C. Wang, Y. Wang, D. Cheng, E. Kong (USTC), Q. Xu et al.*



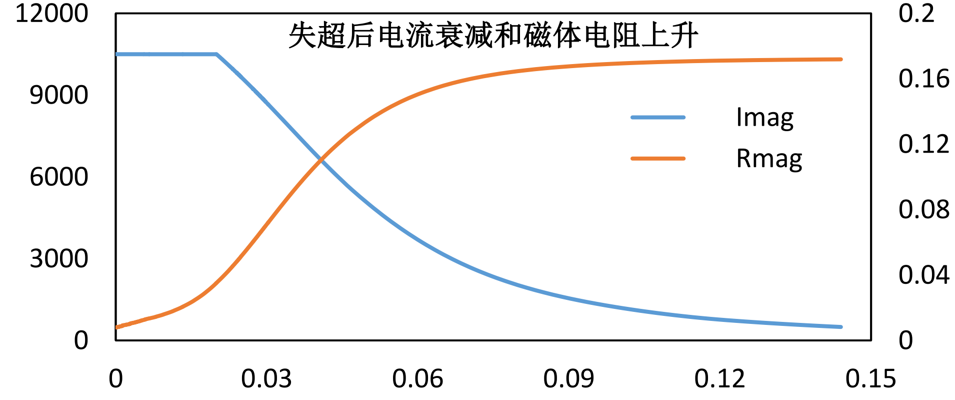
Field distribution in the straight section

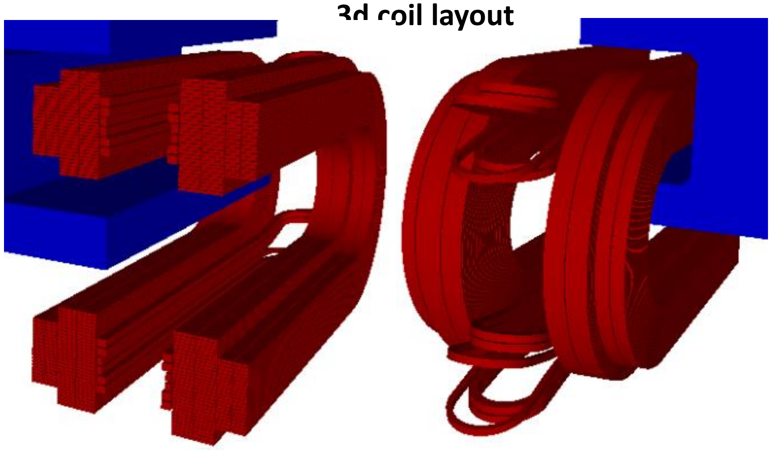




**Clear bore diameter 32mm**
**Inter-aperture spacing 124 mm**

| 运行电流 | 泄能电阻 | 最高温度 | 对地电压 | MIITs | 磁体电阻 |
|---|---|---|---|---|---|
| 10500A | 47mΩ | 252K | 491V | 4.44 | 172mΩ |





3d coil layout

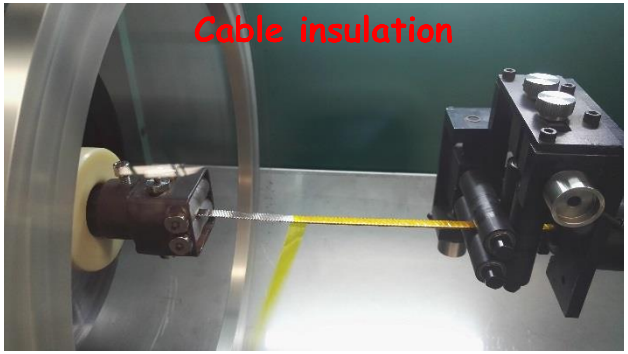
# Superconducting Rutherford Cable R&D

## *Collaboration between WST, Toly Electric and IHEP*

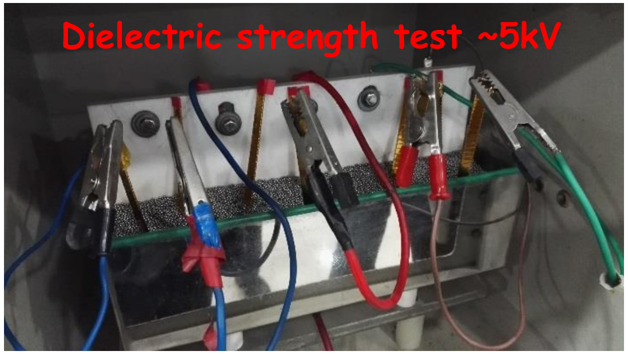
*Y. Zhu (WST), H. Liao (Toly), H. Wang (Changtong), Q.Xu et al.*

~300 m superconducting Rutherford Cable has been fabricated by Toly Electric with WST NbTi strand; $Nb_3Sn$ cable will be fabricated in ~3 months; R&D of Bi-2212 cable to be discussed.

Superconducting Rutherford cable fabricated at Toly with WST strand
0.24% Jc degradation at 7 T with 85% packing factor



Cable insulation



Dielectric strength test ~5kV

Insulated cable

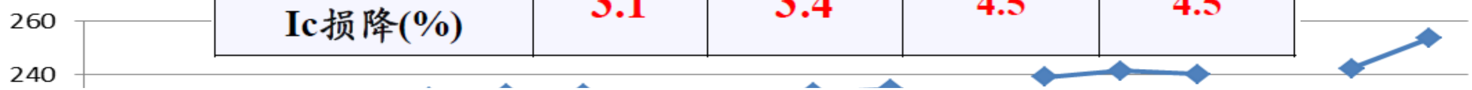
# Superconducting Rutherford Cable R&D

Collaboration between WST, Toly Electric and IHEP

*Y. Zhu (WST), H. Liao (Toly), H. Wang (Changtong), Q.Xu et al.*

| Pitch length | fa | Comments |
|---|---|---|
| 60 | | Not acceptable |
| 45 | | Almost acceptable |
| 52 | | |
| 52 | | Acceptable |

| *NbTi* | 11股*0.70mm | | 11股*0.74mm | |
|---|---|---|---|---|
| 填充率 | 87.0% | | 91.8% | |
| 性能 | Ic（A） | | Ic（A） | |
| | 5T | 7T | 5T | 7T |
| 绞缆前 | 314.8 | 195.6 | 375.2 | 228.4 |
| 绞缆后 | 305.0 | 189.0 | 358.2 | 218.1 |
| 绞缆前后 Ic损降(%) | 3.1 | 3.4 | 4.5 | 4.5 |

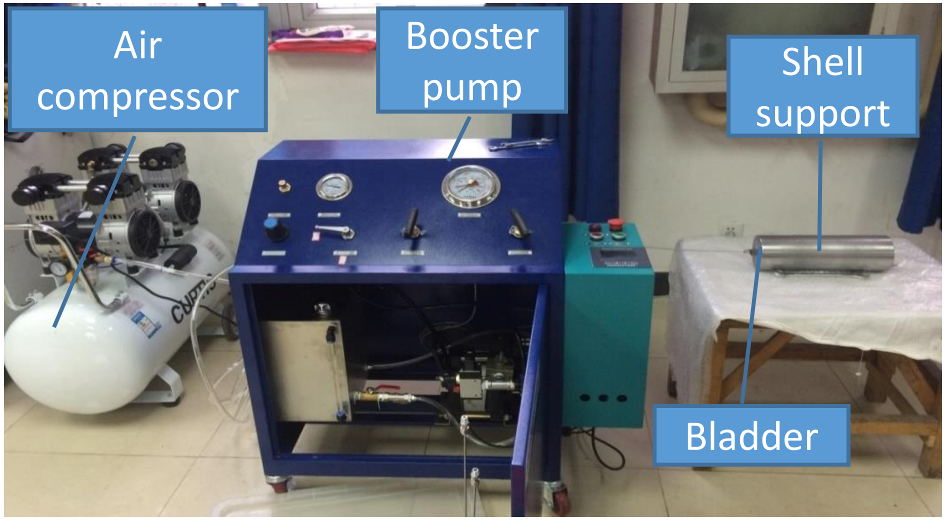


| $Nb_3Sn$ 缆编号 | 填充率 | 线号 | 测试编号 | 绞缆前 Ic(A) | 绞缆后 Ic(A) | Ic损降 (A) | 降幅/% |
|---|---|---|---|---|---|---|---|
| A | 86.5% | 2013-13102B | A-1 | 263 | 248 | 15 | 5.7 |
| C | 91.2% | | C-1 | | 240 | 23 | 8.7 |
| D | 94.7% | | D-1 | | 232 | 31 | 11.8 |
| E | 90.3% | 2013-13104A | E-1 | 258 | 241 | 17 | 6.6 |
| F | 91.3% | | F-1 | | 238 | 20 | 7.8 |

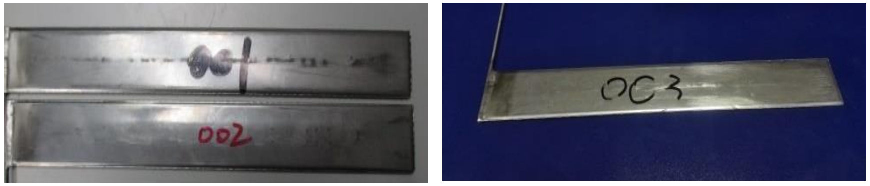
# Development of key components for magnet assembly

*Collaboration between AVIC (中航工业北京航空材料研究院) and IHEP*

*H. Yuan (AVIC), K. Zhang, C. Wang, Y. Wang, D. Cheng, E. Kong (USTC) et al.*

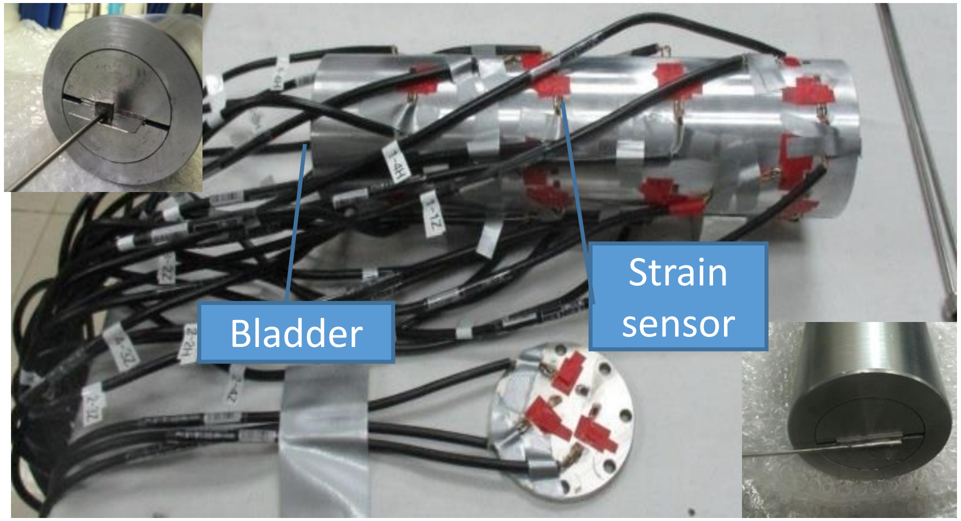


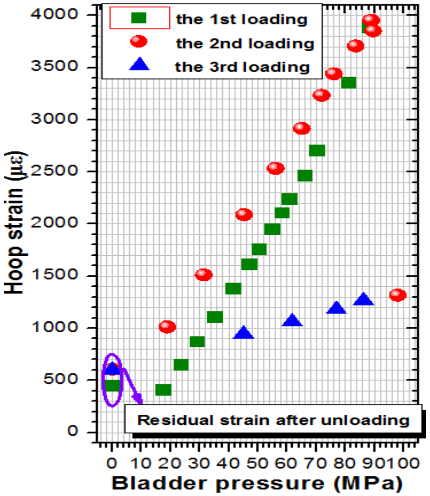
**Test Set-up**



## Test results of bladder 001-005

| Bladder No. | Water pressure（MPa） |
|---|---|
| # 001 | 35 |
| # 002 | 45 |
| # 003 | 26 |
| # 004 | 35 |
| # 005 | 98 |





- Previous thickness of the shim and tube is 0.3 mm.
- Leak always appear at the welding area between the shim and round tube.
- To increase the thickness of the shim and round tube to 0.5 mm for the new bladders.

# Development of key components for magnet assembly

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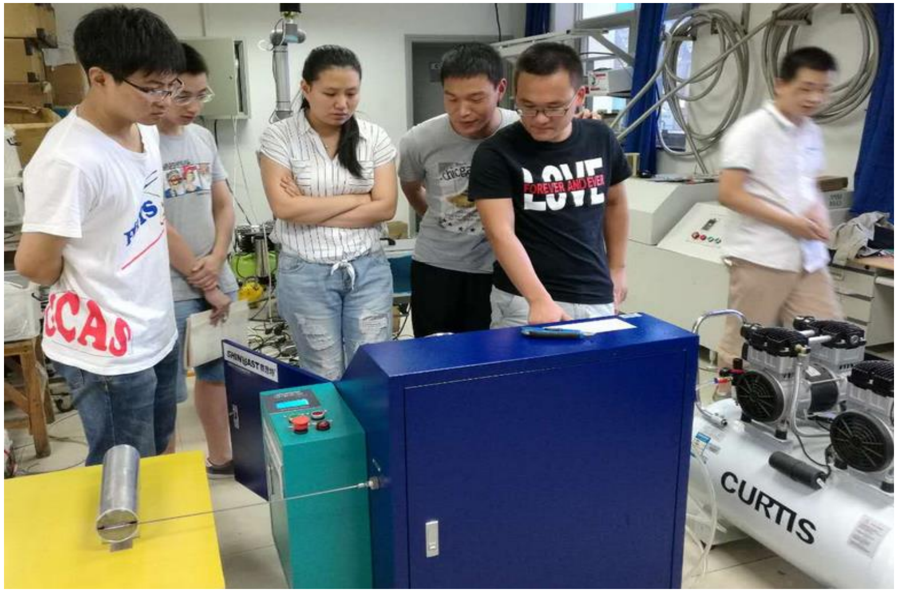
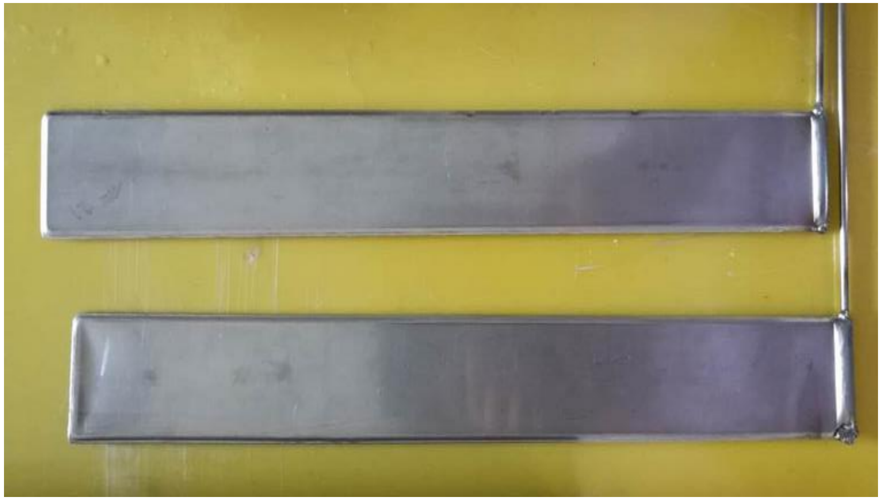


**Latest progress: 102 Mpa achieved!**



Press Control unit

实时压力:102.2MP

保压时间:0000 秒
系统处于空闲状态

# Infrastructure for model coil/magnet fabrication

高场超导线圈/磁体制作平台

**Can wind the coil on horizontal surface, vertical surface or inclined surface (-45~90 degree)**

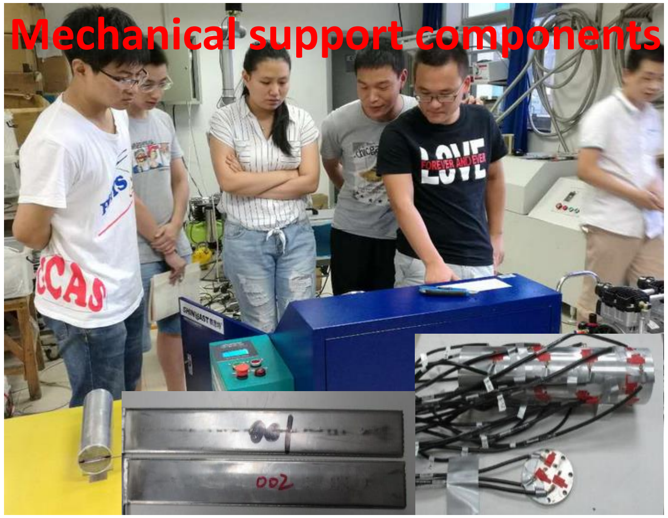

Horizontal surface


Vertical surface


Inclined surface


Practice coil


Vacuum impregnation system


Mechanical support components

# Domestic and International Collaboration

2015 ICFA MINI-WORKSHOP
ON HIGH FIELD MAGNETS FOR PP COLLIDERS
June 14-17th, 2015 Shanghai, China

高温与高场超导材料及其应用技术研讨会
2016.4.28-29 中国 ·上海

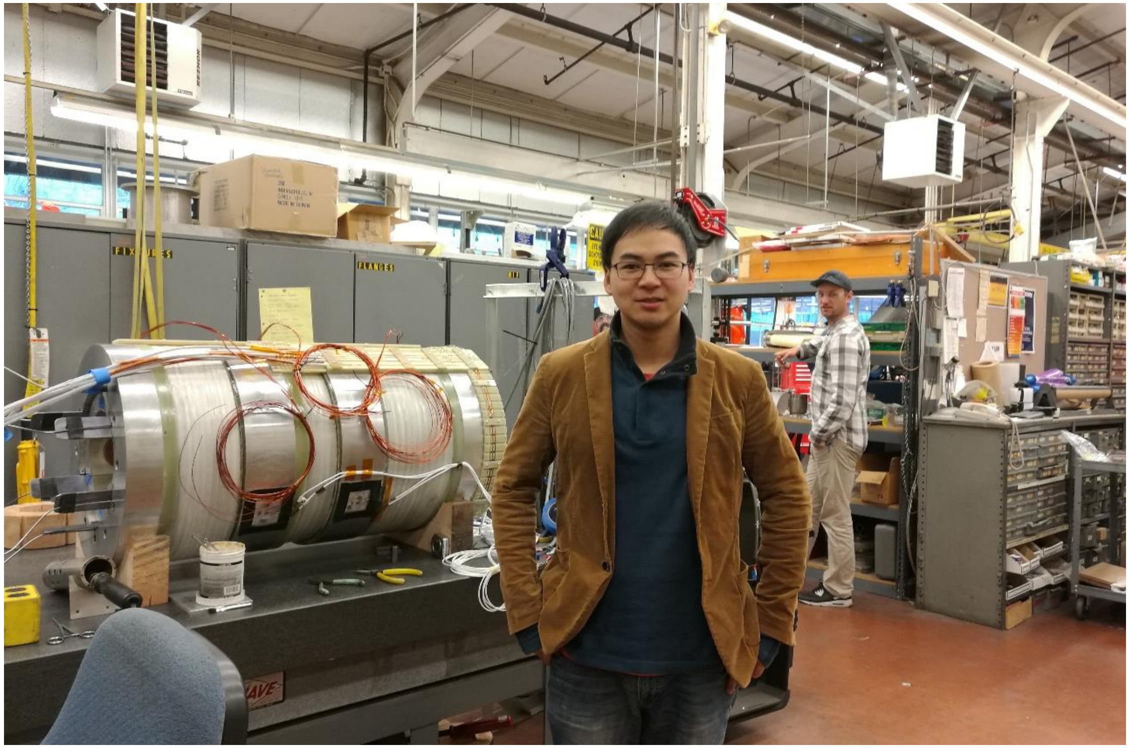
# IHEP & LBNL Collaboration on High Field Magnet R&D

**Progress in 2016:**

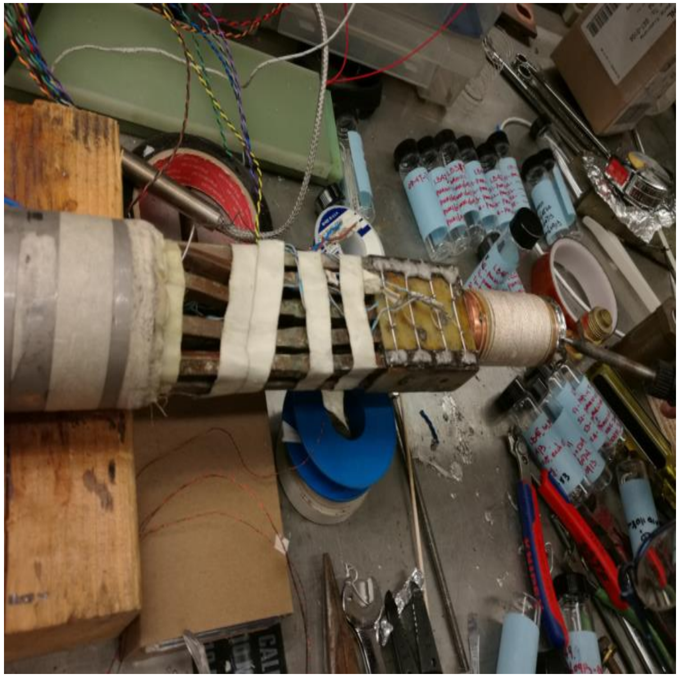
sent a student to LBNL to work with US colleagues on the $Nb_3Sn$ & HTS magnet R&D: Mechanical design study, Jc measurement of superconductors, fabrication and test of HTS coils, …

**Plan for 2017:**

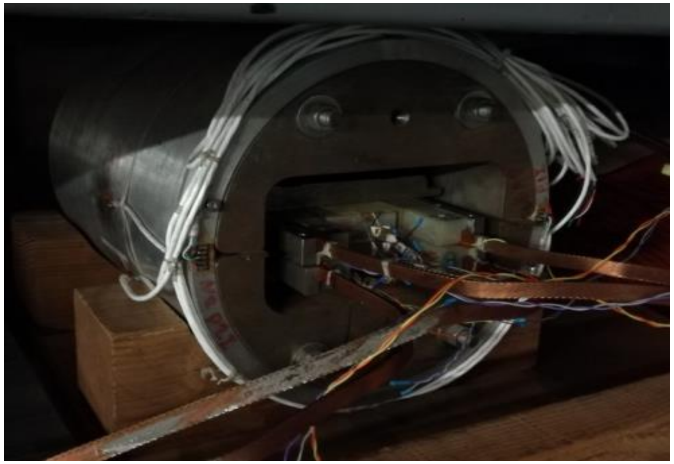
a) Send new students to LBNL for joint-training.
b) Joint efforts on the R&D of $Nb_3Sn$ & HTS magnets.



**Graduate student Kai Zhang stays at LBNL from Oct. 2016 for one year study on high field magnet technology**



**Jc measurement of Bi-2212 short sample**



**Subscale test structure**

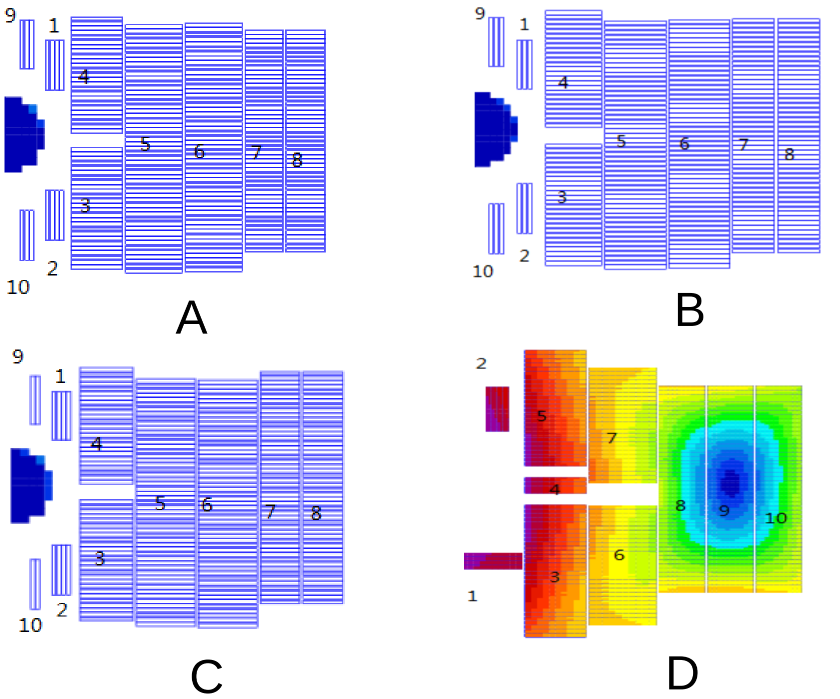
# IHEP & BNL Collaboration on High Field Magnet R&D

**Progress in 2016:**

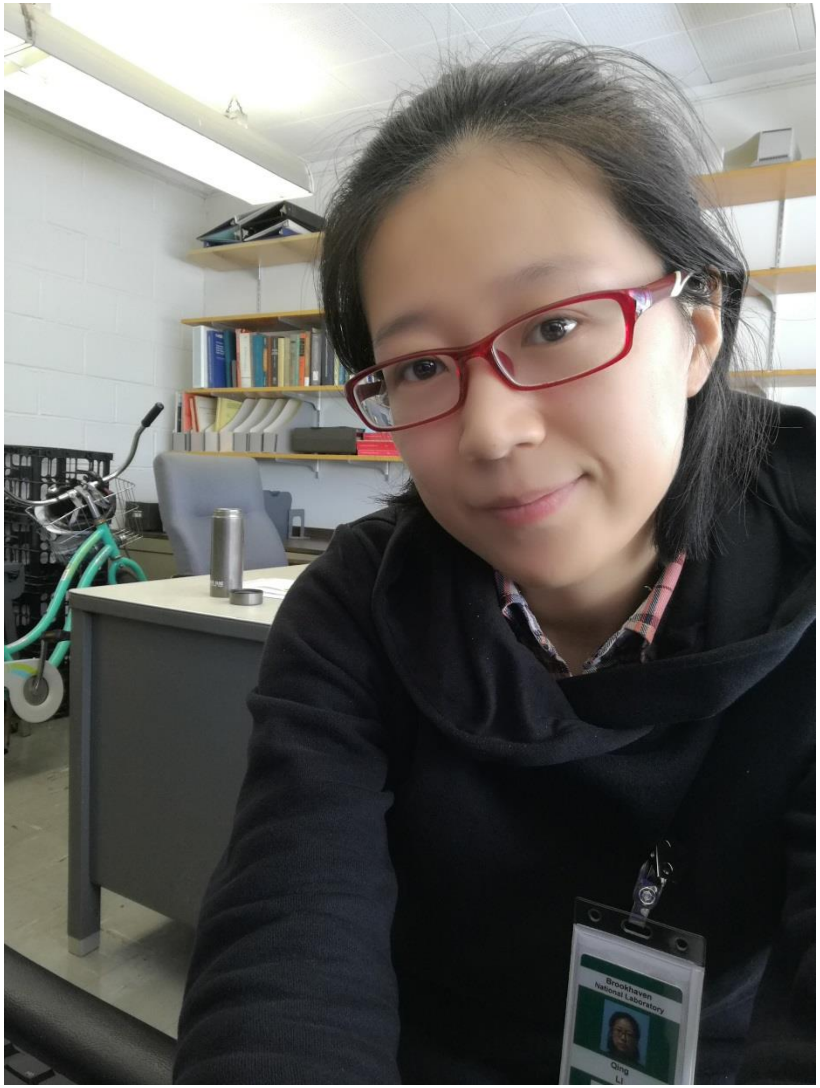
sent a young staff to BNL to work with US colleagues on the design study and coil layout optimization of the 20-T dipole magnets for SPPC.

**Plan for 2017:**

a) Send new staff to BNL for joint-training.
b) Joint efforts on the R&D of the HTS magnets.



**A.** Innermost blocks "3+4" style; **B.** Innermost blocks "3+3" style; **C.** Innermost blocks "2+4" style; **D.** Innermost blocks: one vertical, the other horizontal.



**Qing Li stayed at BNL for one month working with BNL colleagues on the design optimization of the SPPC magnets**

# Summary

- *SPPC needs thousands of high field accelerator magnets to bend and focus the high energy proton beams.*
- *Latest baseline: 12T all-HTS (iron-base superconductor) magnets with 100km circumference and >70TeV center-of-mass energy.*
- *Upgrading phase: 20~24T all-HTS (iron-base superconductor) magnets with 100km circumference and >125TeV center-of-mass energy.*
- *Starting to develop HTS magnet technology before applicable iron-based wire is available (in 5~10 years): model magnet R&D with ReBCO (or Bi-2212) and LTS conductors to study stress management, quench protection, field quality control and fabrication methods.*

***Welcome more collaborators to join us!***

# *Thanks*