SPPC High Field Magnets - Preliminary Design Study and R&D Steps

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Requirements 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**
- Field strength: 20 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

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

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

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

**WHOLE WIRE** critical current density of main superconductors @ 4.2 K

<table>
<thead>
<tr>
<th>Material</th>
<th>Critical Current Density @ 4.2 K (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti</td>
<td>11 T @ 1.9K</td>
</tr>
<tr>
<td>Nb$_3$Sn (Nb$_3$Al)</td>
<td>17 T @ 4.2 K</td>
</tr>
</tbody>
</table>

Why?

- Nb-Ti: 11 T @ 1.9K
- Nb$_3$Sn (Nb$_3$Al): 17 T @ 4.2 K
Why 20-T Dipole Is Difficult?

### Dipole vs Solenoid

- Different coil configurations
  \[ B_{\text{dipole}} = \frac{1}{2} B_{\text{solenoid}} \]
- Limited coil width for dipole
- Magnetic shielding
- Cost

### Solenoid

\[ B = \mu_0 J_e t \]

### Dipole

\[ B = \mu_0 J_e \frac{t}{2} \]

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Martin Wilson, ‘Pulsed Superconducting Magnets’ CERN Academic Training May 2006
Status of Nb$_3$Sn Accelerator Magnet R&D

Results achieved with Nb$_3$Sn dipole technology test
- 16 T achieved with block type configuration (HD1 @ LBNL, 2003)
- 15 T achieved with common coil configuration (RD3 @ LBNL, 2001)

Results achieved with accelerator level field quality and bore
- 14 T achieved with block type configuration (HD2 @ LBNL, 2007)
- 13 T achieved with Cos-theta configuration (D20 @LBNL, 1997)

Challenges and R&D Focus
of the 20-T Accelerator Magnets

- **J<sub>c</sub> and cost of Superconductors**: Based on the present J<sub>c</sub> level, thousands of tons of Nb<sub>3</sub>Sn and HTS superconductors are needed to fabricate SPPC magnets. Significant increase of J<sub>c</sub> and reduction of cost of superconductors are expected.

- **HTS coils for accelerator magnets**, especially tape conductors: field quality (current distribution, magnetization effect,...), quench protection and fabrication method.

- **Magnetic force in superconducting coils at 20 T**: \( F \sim B^2 \). And both Nb<sub>3</sub>Sn and HTS superconductors are strain sensitive! Needs innovative strain management in coils.

- **Twin aperture 20-T magnets with limited outer diameter**: cross-talk between the two apertures, iron saturation, magnetic shielding... Needs smart magnetic and mechanical design.
**Design Study of the SPPC Dipole Magnet**

*With common coil configuration*

20-T dipole magnet with common coil configuration

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

\[ B_y = \frac{\mu_0 I}{2\pi} \int_{-b/2}^{b/2} \ln \left( \frac{(a+d)^2+y_0^2}{(a+d/2)^2+y_0^2} \right) \frac{(m+b-y_0)^2}{(a+d/2)^2+(m+b-y_0)^2} \, dy_0 \]

20-T common coil dipole magnet: space for beam pipes: 2 * Φ50 mm,
with the load line ratio of ~80% @ 1.9 K

Design Study of the SPPC Dipole Magnet

With common coil configuration

20-T dipole magnet with common coil configuration
two Φ50 mm beam pipes; load line 80% @ 1.9 K

Q. Xu et al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., to be published
Design Study of the SPPC Dipole Magnet

Lorentz force per aperture:
\[ F_{\text{mag}_x} = 23.4 \text{ MN/m} \]
\[ F_{\text{mag}_y} = 2.38 \text{ MN/m} \]

Stress in coil after excitation

Stress in shell after excitation

R&D Steps for SPPC Dipole Magnets

1st step  
*ongoing*
Fabrication of a 15-T Nb$_3$Sn or Nb$_3$Sn+HTS subscale magnet, to test the stress management method for Nb$_3$Sn & HTS coils and the quench protection method for HTS coils;

Available budget: 3 million RMB. By the end of 2018.

2nd step
Fabrication of a 15-T Nb$_3$Sn or Nb$_3$Sn+HTS operational field dipole magnet with two Φ50 mm beam pipes and 10$^{-4}$ field quality, to test the field optimization method for HTS coils;

To be funded.

3rd step
Fabrication of the 20-T magnet with Nb$_3$Sn+HTS or only one of them, if we can get significant progress on the performance of Nb$_3$Sn or HTS superconductors, i.e., their Jc level is 3~6 times increased or even more, and the cost is significantly reduced.
R&D Steps for SPPC Dipole Magnets

Comparison of different coil configurations

Efficiency, field quality, stress management, fabrication method...

- **Cos-theta dipole**
  Higher efficiency, complicated ends with hard-way bending

- **Common coil dipole**
  Simplest structure with large bending radius, lower efficiency

- **Block type dipole**
  Simpler structure with hard-way bending, lower efficiency

- **Canted cos-theta dipole**
  Lowest stress level in coil, lowest efficiency
R&D Steps for SPPC Dipole Magnets

Comparison of different coil configurations

Common coil vs Cos-theta

C. Wang et al.

Different coil configurations for 20-T dipole magnet

Left: Common coil
Right: Cos-theta

Common coil

Coil ends

Cos-theta
R&D Stpes for SPPC Dipole Magnets

R&D of advanced superconductors: Nb$_3$Sn & HTS

Super High $J_c$ Nb$_3$Sn

Magnet field Vs. Conductor $J_c$

Over-pressure HTS Bi-2212

Principle: increase of Nb$_3$Sn pinning force at high field through grain refinement: $J_c(12$ T, 4.2K) from 3.5 kA/mm$^2$ @ 100+ nm to 9.6 kA/mm$^2$ @ 35 nm!

X. Xu et al, Appl. Phys. Lett. 104 082602 & ASC14


D. C. Larbalestier et al, NATURE MATERIALS
DOI: 10.1038/NMAT3887, 2014
**R&D Steps for SPPC Dipole Magnets**

**High $J_c$ Nb$_3$Sn development at WST**

### Nb$_3$Sn/Cu 及 NbTi/Cu 超导线订货合同

<table>
<thead>
<tr>
<th>合同号</th>
<th>名称</th>
<th>牌号</th>
<th>规格型号</th>
<th>长度</th>
<th>单价 (元/米)</th>
<th>金额 (元)</th>
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<td>超导线</td>
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<td>6000 米</td>
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<tr>
<td>W201503026</td>
<td>超导线</td>
<td>NbTi/Cu</td>
<td>Φ0.820mm</td>
<td>6000 米</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

合计人民币大写：合同总价: 

**注：单价为含税价格。**

二、质量技术标准：

Nb$_3$Sn/Cu 超导线：

1. Cu:Sc=1.0(+/-0.1)
2. 线径尺寸：0.820（+/-0.005）mm
3. RRR(273K/20K)：>70
4. 临界电流（12T,4.2K）：>660A
5. 表面镀层：Cr
6. 镀层厚度：1~2μm
7. 长度要求：单根长度大于350m，可以倍尺交货。

NbTi/Cu 超导线：

1. Cu:Sc=1.5(+/-0.1)
2. 线径尺寸：0.820（+/-0.005）mm
3. RRR(273K/10K)：>100
4. 临界电流（5T,4.2K）：>450A

~ Non-Cu $J_c > 2500$ A/mm$^2$ @ 12 T, 4.2 K !

Available soon!
R&D Steps for SPPC Dipole Magnets

**Build-up of lab infrastructure and equipment**

(Assume with enough funding)

- **Superconductor cabling**
  - Rutherford Cabling @ Fermilab

- **Advanced insulation**
  - AGY S2-glass fibers insulation

- **Coil fabrication**
  - Nb3Sn coil winding @ CERN

- **Magnet assembly & test**
  - Magnet test facility @ CERN

- **Coil impregnation**
  - Epoxy impregnation system @ KEK

- **Coil heat reaction**
  - Nb3Sn coil reaction @ CERN
R&D Steps for SPPC Dipole Magnets

Development of a Rutherford cabling machine

Why Rutherford cable instead of single wire?
- Reduction of the strand piece length;
- Reduction of the coil inductance;
- Current redistribution in case of a defect in one strand;
- Twisted strands to reduce interstrand coupling losses and field distortions, and provide more mechanical stability.

Ezio Todesco, USPAS 2012

24 Φ0.727 NbTi strands with/without Sn coating

(Short sample superconducting Rutherford cables fabricated by Changtong and Toly)
20-T Magnet Working Group in China

Northwest Institute for Non-ferrous Metal Research (NIN, Xi’an) & Western Superconducting Tech. Co, Ltd (WST, Xi’an)
Qualified Nb$_3$Sn supplier for ITER; R&D and production of High J$_c$ Nb$_3$Sn and Bi-2212 superconductors.

Shanghai JiaoTong U.& Shanghai Superconductor Tech. Co., Ltd (SSTC, Shanghai)
R&D and production of ReBCO superconductor.

Tsinghua U. & Innova Superconductor Tech. Co., Ltd (INNOST, Beijing)
R&D and production of Bi-2223 superconductor.

Institute of Plasma Physics, Chinese Academy of Sciences (IPP, Hefei)
Test stand with 12-T background field, Nb$_3$Sn CICC cable fabrication;...

High Magnetic Field Laboratory, Chinese Academy of Sciences (CHMFL, Hefei)
Development of High field solenoids;...

Institute of High Energy Physics, Chinese Academy of Sciences (IHEP, Beijing)

Accelerator Center Magnet Group: 30+ years R&D and production of conventional accelerator magnets.

Superconducting Magnet Engineering Center: 10+ years R&D and production of superconducting solenoids for particle detectors and industries.

and USTC, IMP, CIAE...

Seeks new members to join us!
20-T Magnet Working Group in China
International Collaboration

2015 ICFA MINI-WORKSHOP ON HIGH FIELD MAGNETS FOR PP COLLIDERS

June 14-17th, 2015  Shanghai, China

Organizer: Insitute of High Energy Physics Chinese Academy of Sciences
Co-organizer: Shanghai Superconductor Technology Co., Ltd.
Summary

• **SPPC needs thousands of 20-T level magnets to bend and focus the high energy proton beams**.

• **Present status of the accelerator magnet technology: highest 16 T achieved to demonstrate the Nb$_3$Sn technology but without accelerator level bore and field quality. Present highest operational field for accelerators 8.3 T.**

• **To achieve the challenging 20-T accelerator magnets, a 10~15 years long term R&D is necessary. A 3-step R&D roadmap is proposed.**

• **A working group is being organized for the 20-T magnet R&D in China, and expecting international collaboration with worldwide labs.**

• **Design study is ongoing to finish the CDR by end of 2016.**

• **Funding application is ongoing to carry out the R&D of this critical technology for CEPC-SPPC.**
Thanks