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

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On behalf of the SppC magnet working group

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2016.9.2

Outline

- Concept of the 20T Dipole Magnet for SPPC
- R&D Steps for 20T Dipole Magnet
- Development Status
- National Collaboration
- International Collaboration
- Next steps

Concept of the 20T Dipole Magnet for SPPC

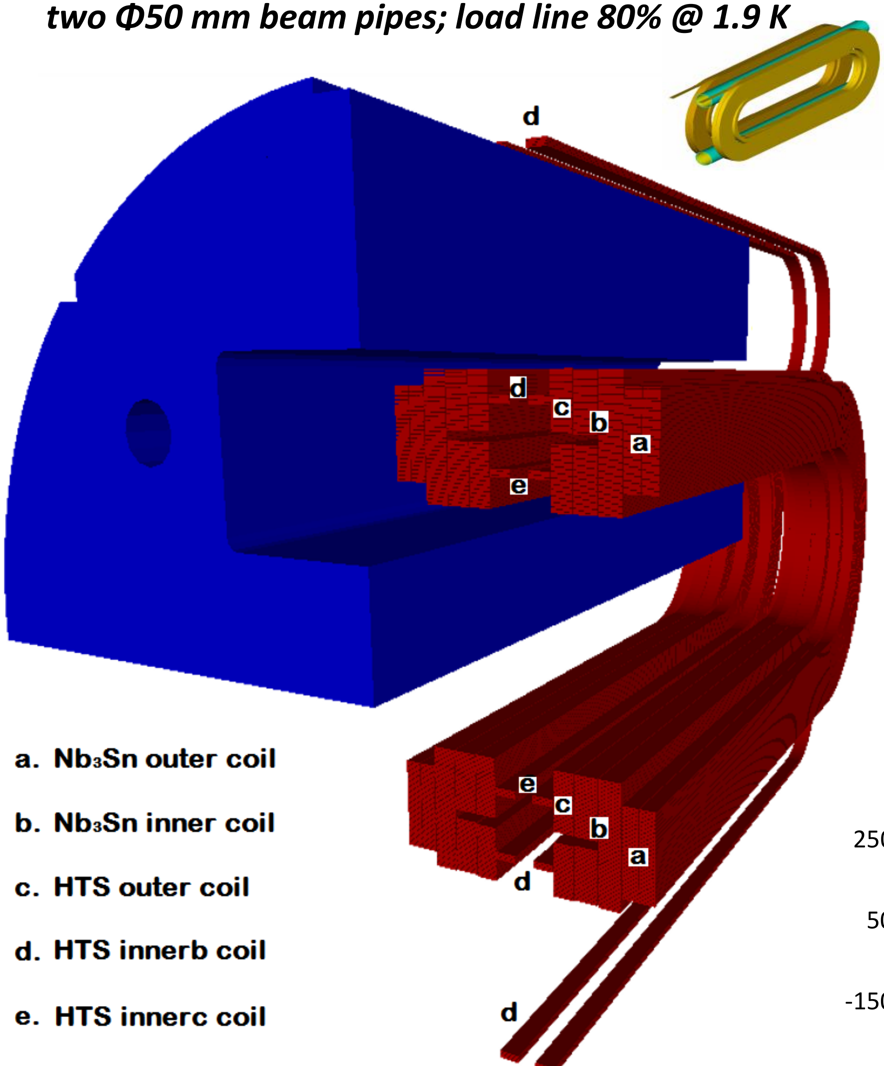
Q. Xu et al.

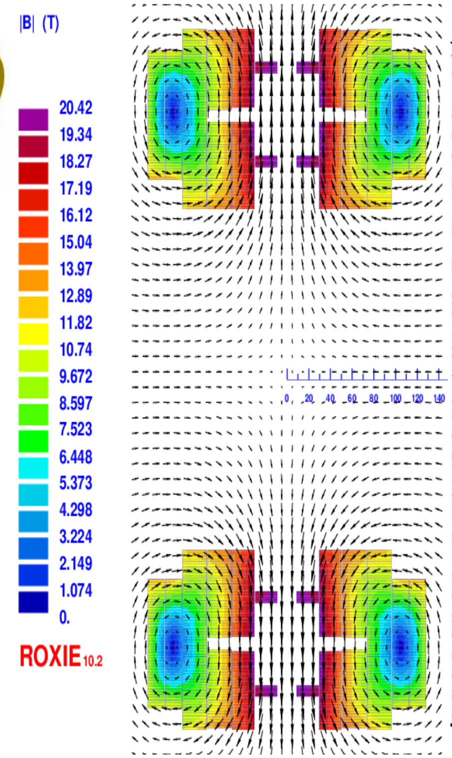
With common coil configuration

Reminder

20-T dipole magnet with common coil configuration

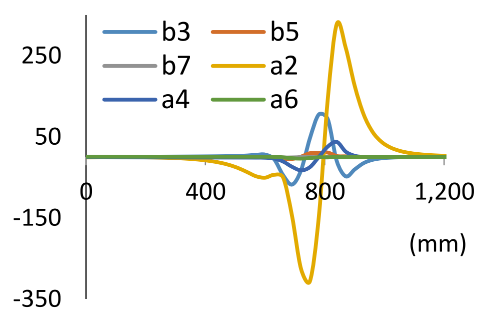
two Φ50 mm beam pipes; load line 80% @ 1.9 K





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

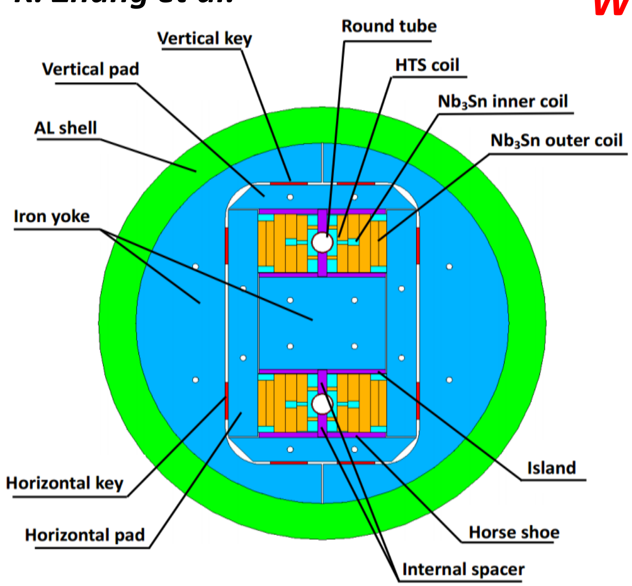
Integrated b_n & a_n	Value (10^{-4})
b3	0.14
b5	1.42
b7	-0.40
a2	-0.29
a4	-1.81
a6	0.03

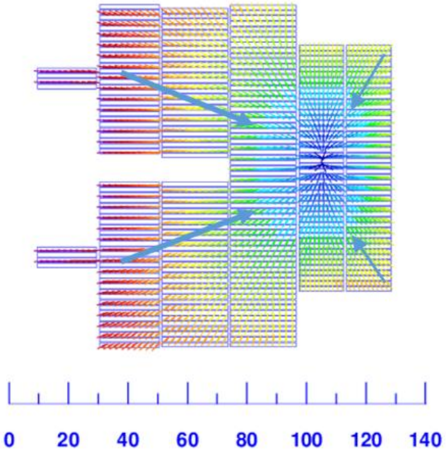
Q. Xu et. al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016，4000404

Concept of the 20T Dipole Magnet for SPPC

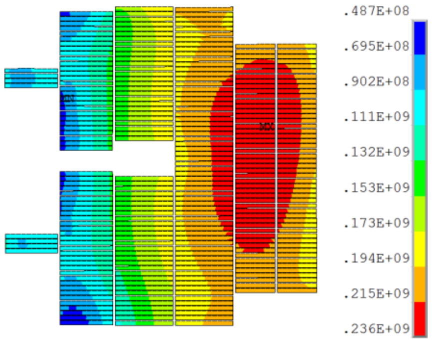
K. Zhang et al.

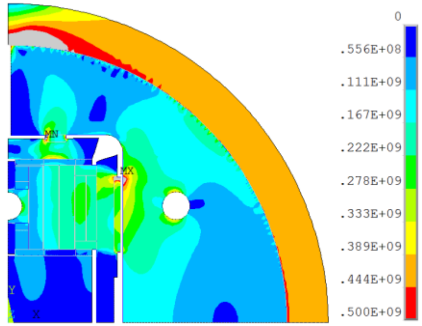
With common coil configuration





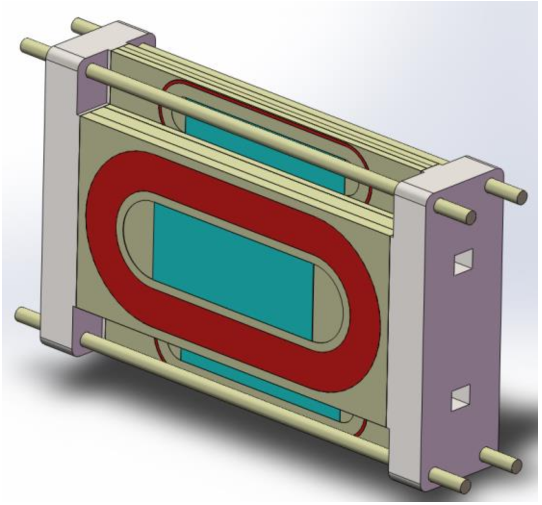
Lorentz force per aperture:
Fx=23.4 MN/m ; Fy=2.38 MN/m

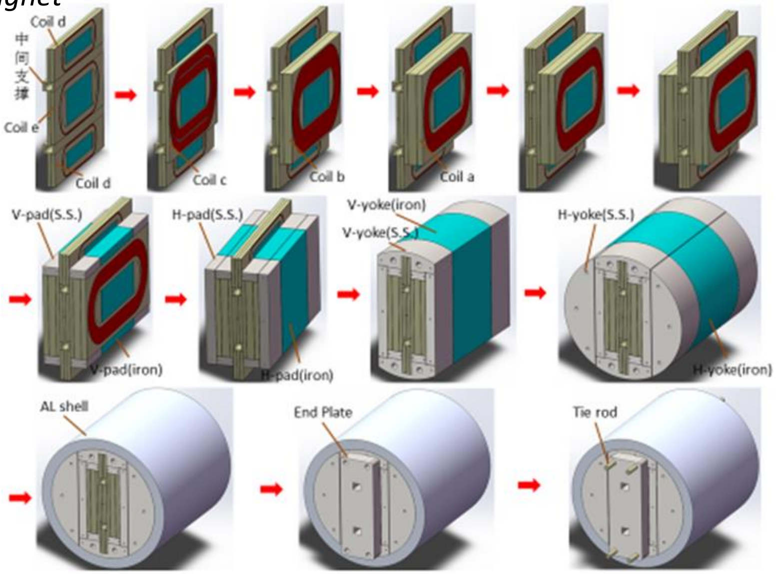


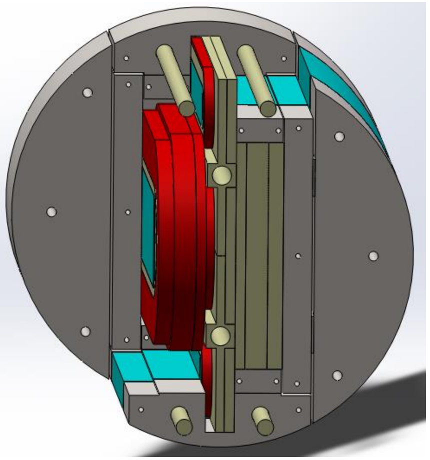


Stress distribution after excitation

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







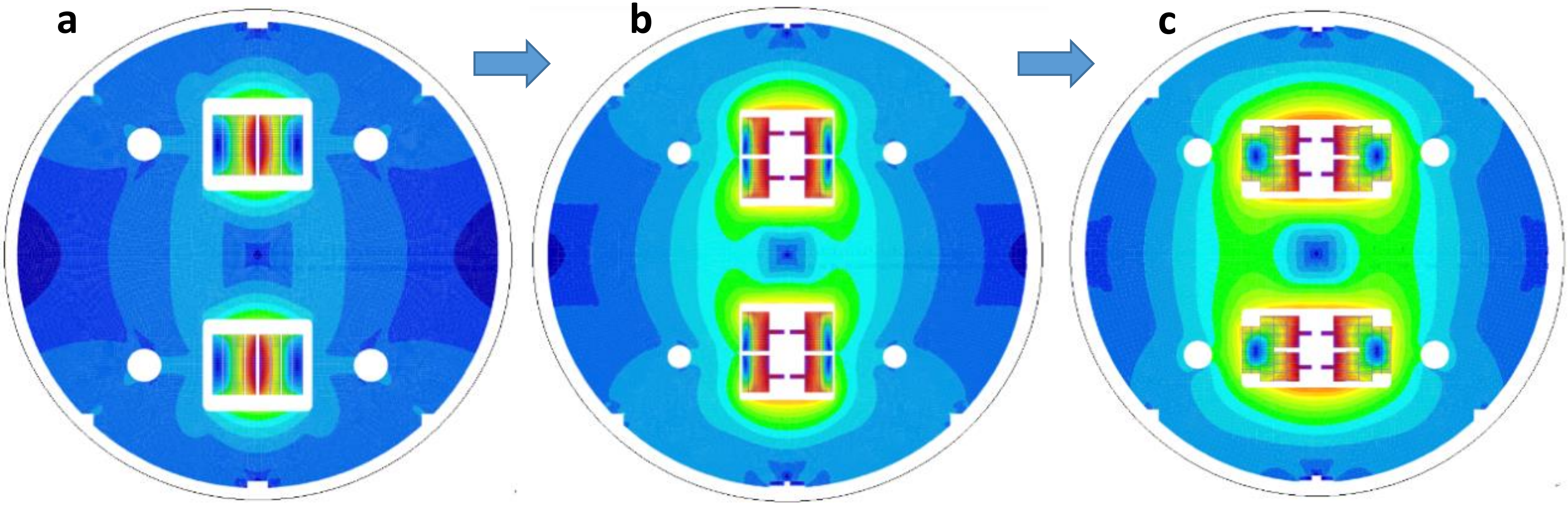
K. Zhang et. al., 2-D Mechanical Design Study of a 20-T Two-in-One Common-Coil Dipole Magnet for High-Energy Accelerators, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016, 4003705

R&D Steps for 20T Dipole Magnet

Q. Xu et al.

With common coil configuration

Reminder



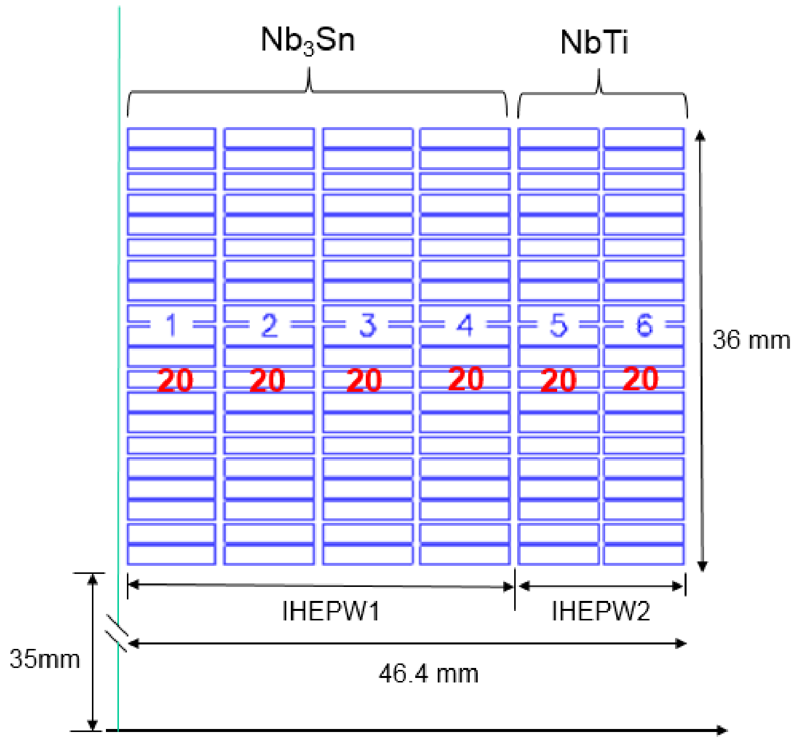
1^{st} step ***ongoing***	***2^{nd} step***	***3^{rd} step***
Fabrication of 15-T Nb_3Sn and Nb_3Sn+HTS subscale magnets, to test the stress management method for Nb_3Sn & HTS coils and the quench protection method for HTS coils;	***Fabrication of 15-T Nb_3Sn and Nb_3Sn+HTS operational field dipole magnet with two Φ50 mm beam pipes and 10^{-4} field quality, to test the field optimization method for HTS coils;***	***Fabrication of the 20-T magnet with Nb_3Sn+HTS or only one of them, if we can get significant progress on the performance of Nb_3Sn or HTS superconductors, i.e., their Jc level is 3~6 times increased or even more, and the cost is significantly reduced.***
By the end of 2018.	***To be funded.***	

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

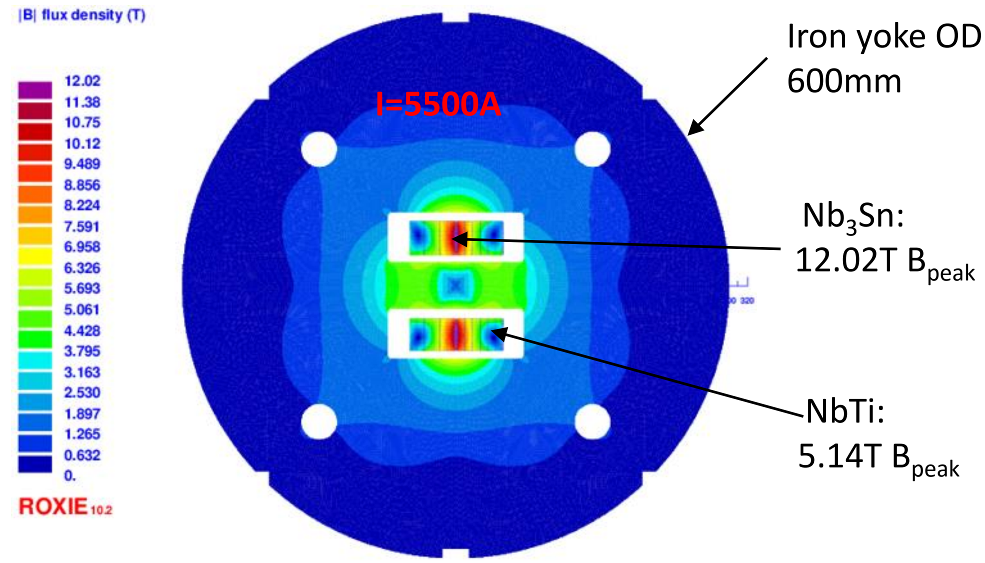
R&D Steps for 20T Dipole Magnet 2016-18

C. Wang, K. Zhang et al.

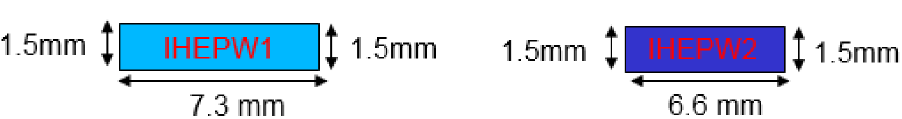
1. A 14-T subscale magnet to be fabricated with Nb_3Sn and NbTi superconductors in 2016, to investigate the fabrication process and mechanical characteristics of Nb_3Sn coils.



Coil configuration in the 1st quadrant



2D Field distribution



For per meter of such magnet, the required length of the strand: Nb_3Sn: 5.76 Km; NbTi: 2.24Km.

Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IHEPW1	7.3	1.5	1.5	18	IHEPWCJC	Nb3Sn	0.15
IHEPW2	6.6	1.5	1.5	16	IHEPWNJC	NbTi	0.15

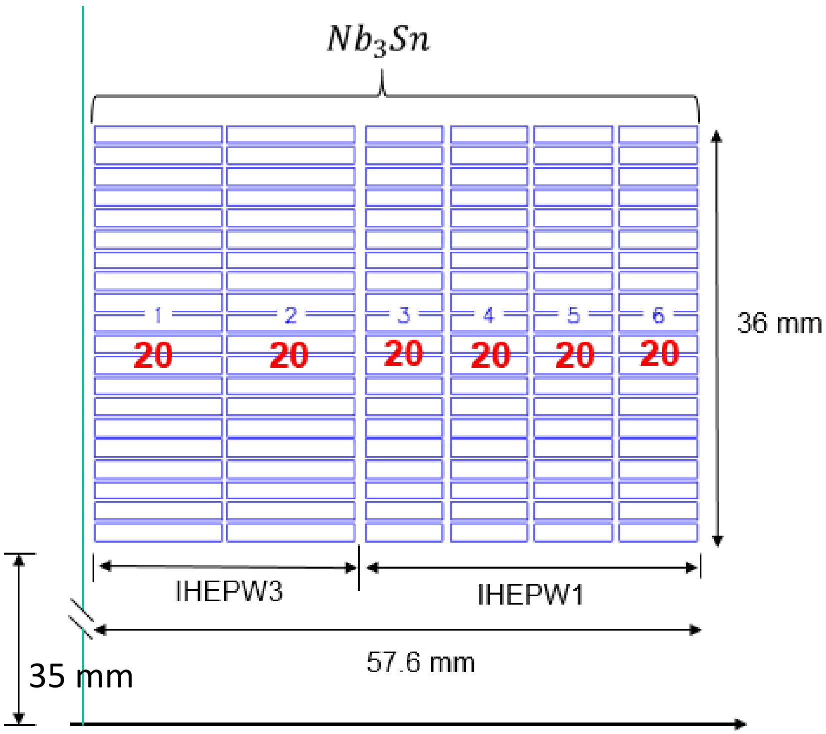
Main parameters of the strands

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IHEPWCJC	0.802	1	200	4.2	12	2700	400
IHEPWNJC	0.82	1.6	130	4.2	5	2954	550

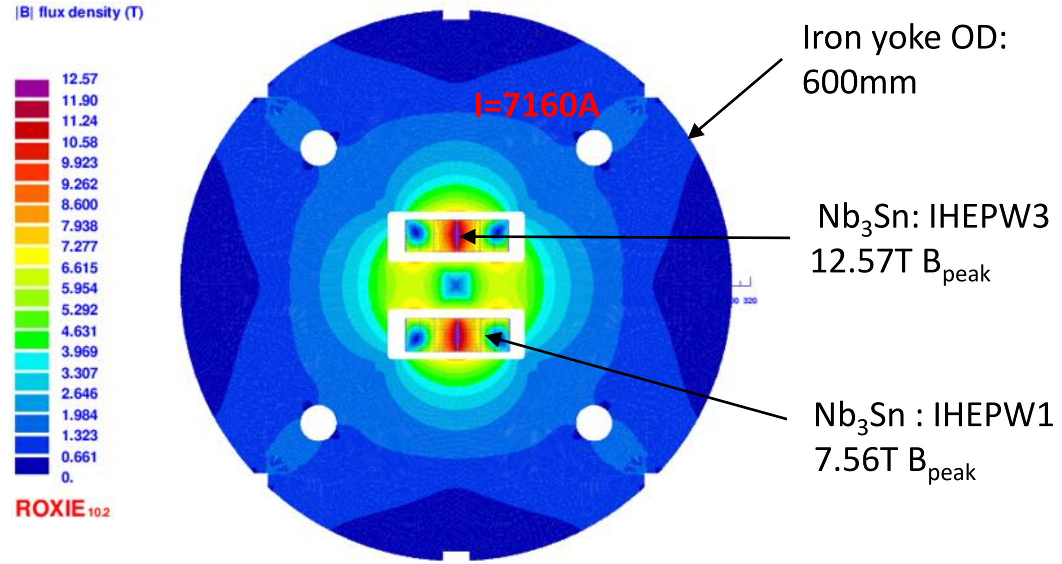
R&D Steps for 20T Dipole Magnet 2016-18

C. Wang, K. Zhang et al.

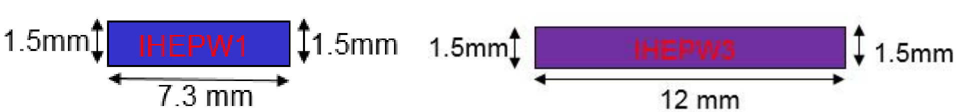
2-1. A 15-T subscale magnet to be fabricated with only Nb_3Sn superconductors but different cable dimensions, to test the stress management method of Nb_3Sn coils.



Coil configuration in the 1st quadrant



2D Field distribution



For per meter of such magnet, the required length of the strand: Nb_3Sn in total: 10.4 Km.

Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IHEPW1	7.3	1.5	1.5	18	IHEPWCJC	Nb3Sn	0.15
IHEPW3	12	1.5	1.5	29	IHEPWCJC	Nb3Sn	0.15

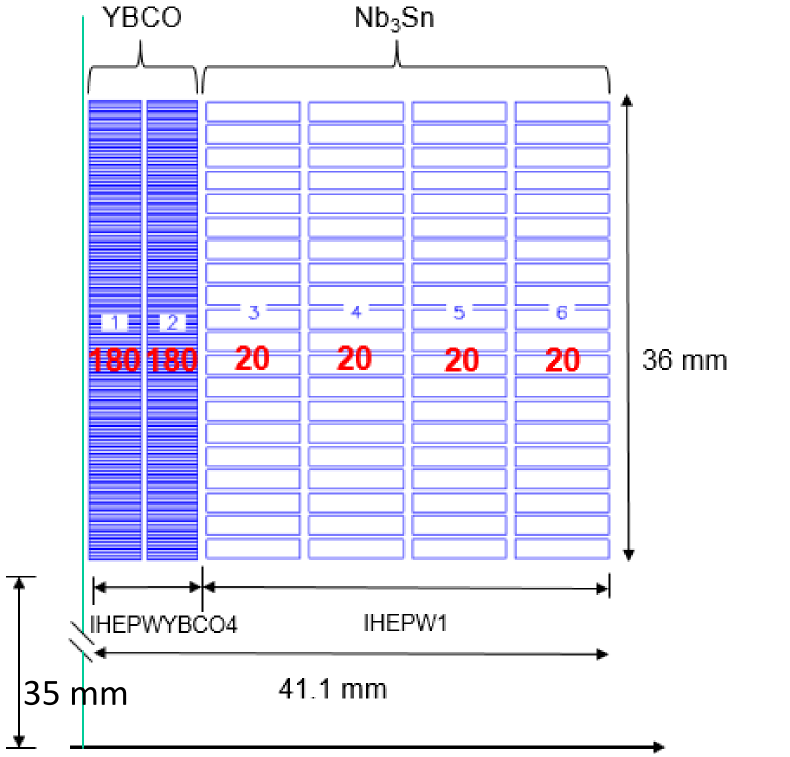
Main parameters of the strands

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IHEPWCJC	0. 802	1	200	4. 2	12	2700	400

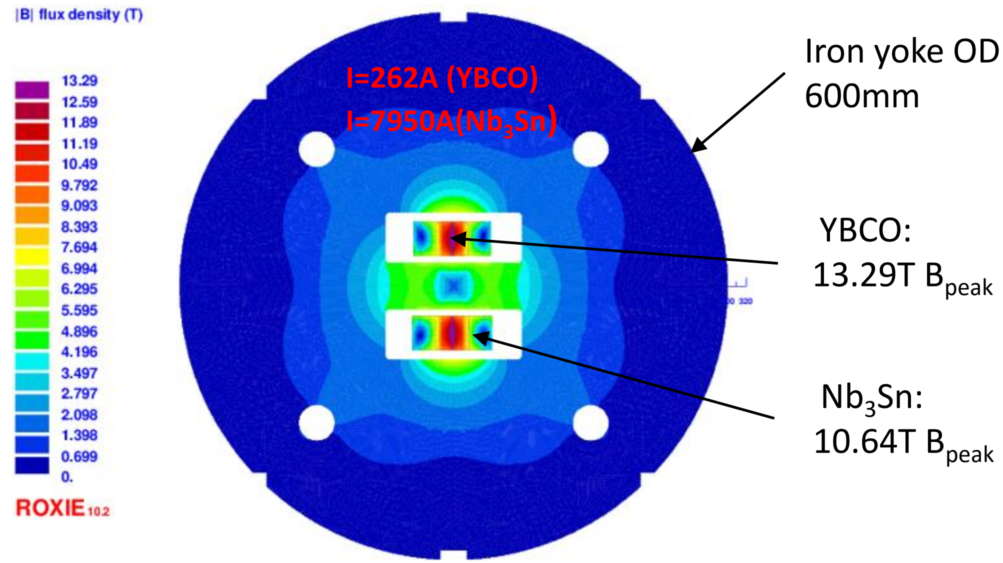
R&D Steps for 20T Dipole Magnet 2016-18

C. Wang, K. Zhang et al.

2-2. A 16-T subscale magnet will be fabricated with HTS and Nb_3Sn superconductors, to test the stress management method and quench protection method of HTS coils.



Coil configuration in the 1st quadrant



Field distribution in the cross section of this common-coil dipole

Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IHEPW1	7.3	1.5	1.5	18	IHEPWCJC	Nb3Sn	0.15
IHEPWYBCO4	4	0.2	0.2	1	IHEPWYBCO	YBCO	0

Main parameters of the strands

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IHEPWCJC	0.802	1	200	4.2	12	2700	400
IHEPWYBCO	–	–	–	4.2	12	1020	40

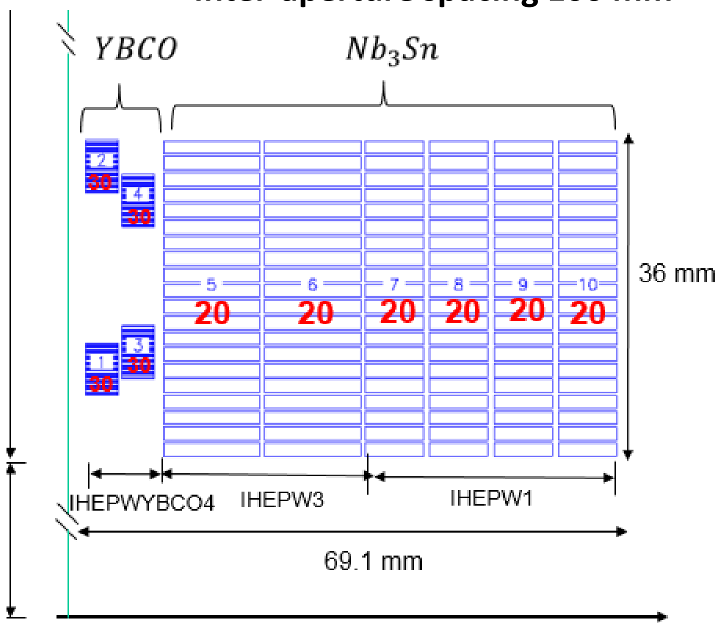
For per meter of such magnet, the required length of the strand: YBCO: 1.44Km; Nb_3Sn: 5.76 Km

R&D Steps for 20T Dipole Magnet 2016-18

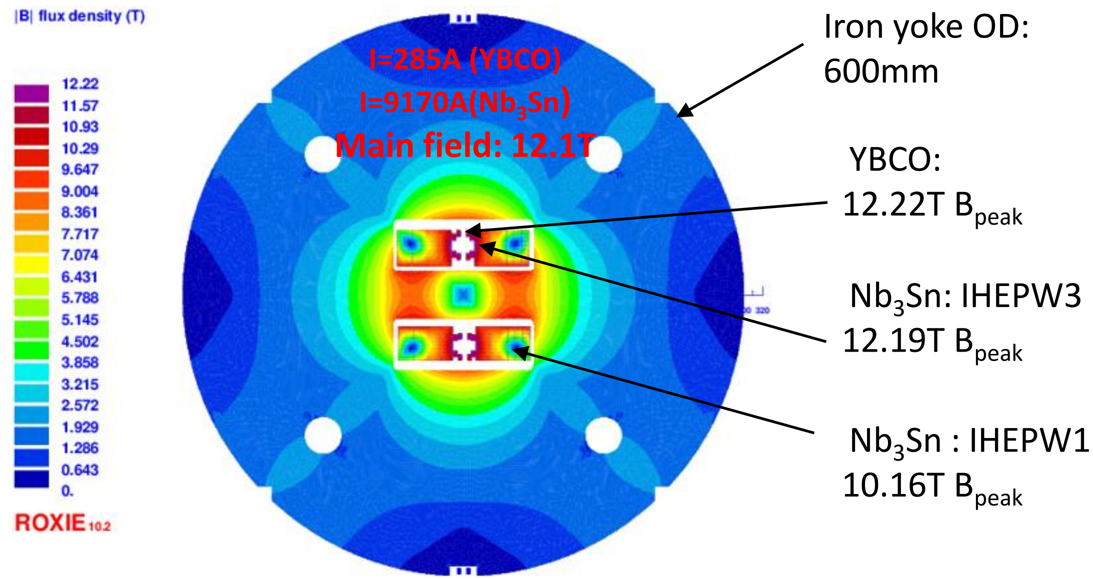
C. Wang, K. Zhang et al.

3. To fabricate a 14-T dipole magnet (with two apertures) with HTS and Nb_3Sn superconductors, to test the field optimization method of HTS & Nb_3Sn coils.

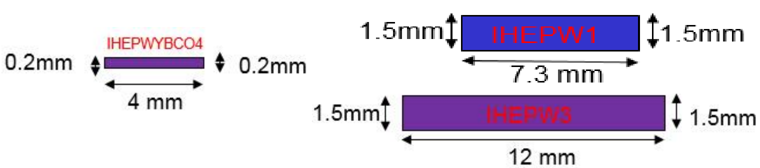
Clear bore diameter 15mm
Inter-aperture spacing 106 mm



Coil configuration in the 1st quadrant



2D Field distribution



For per meter of such magnet, the required length of the strand: YBCO: 0.6 Km; Nb_3Sn in total: 10.4 Km

Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IHEPW1	7.3	1.5	1.5	18	IHEPWCJC	Nb3Sn	0.15
IHEPW3	12	1.5	1.5	29	IHEPWCJC	Nb3Sn	0.15
IHEPWYBCO4	4	0.2	0.2	1	IHEPWYBCO	YBCO	0

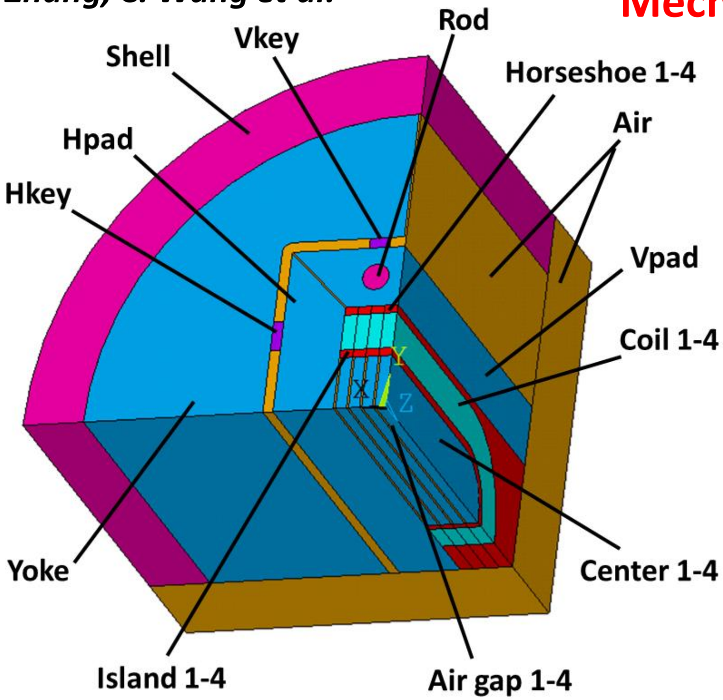
Main parameters of the strands

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IHEPWCJC	0.802	1	200	4.2	12	2700	400
IHEPWYBCO	–	–	–	4.2	12	1020	40

R&D Steps for 20T Dipole Magnet 2016-18

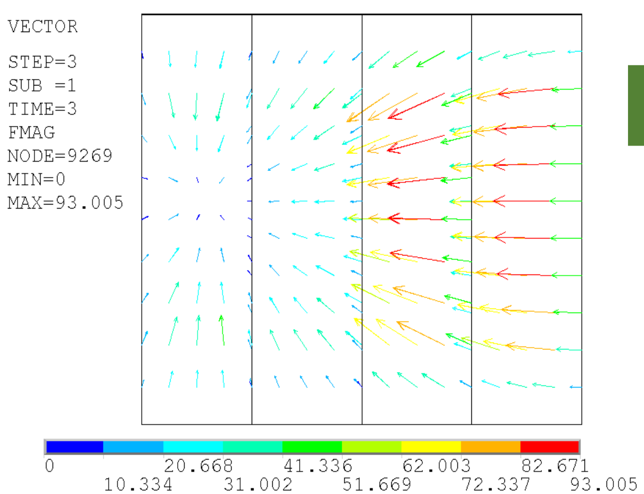
K. Zhang, C. Wang et al.

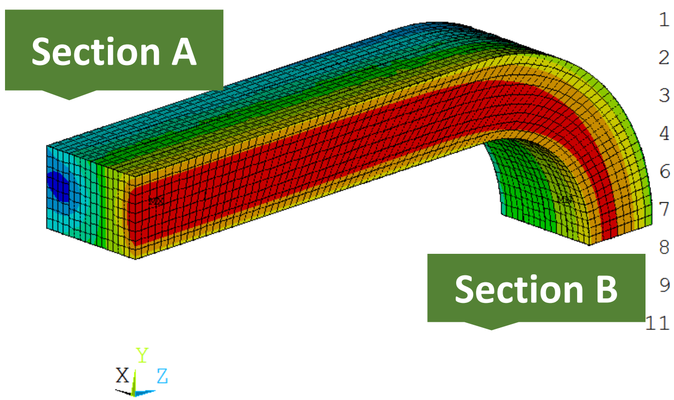
Mechanical analysis

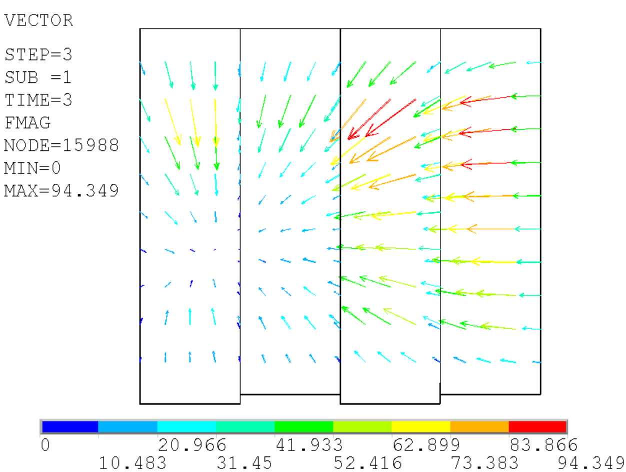


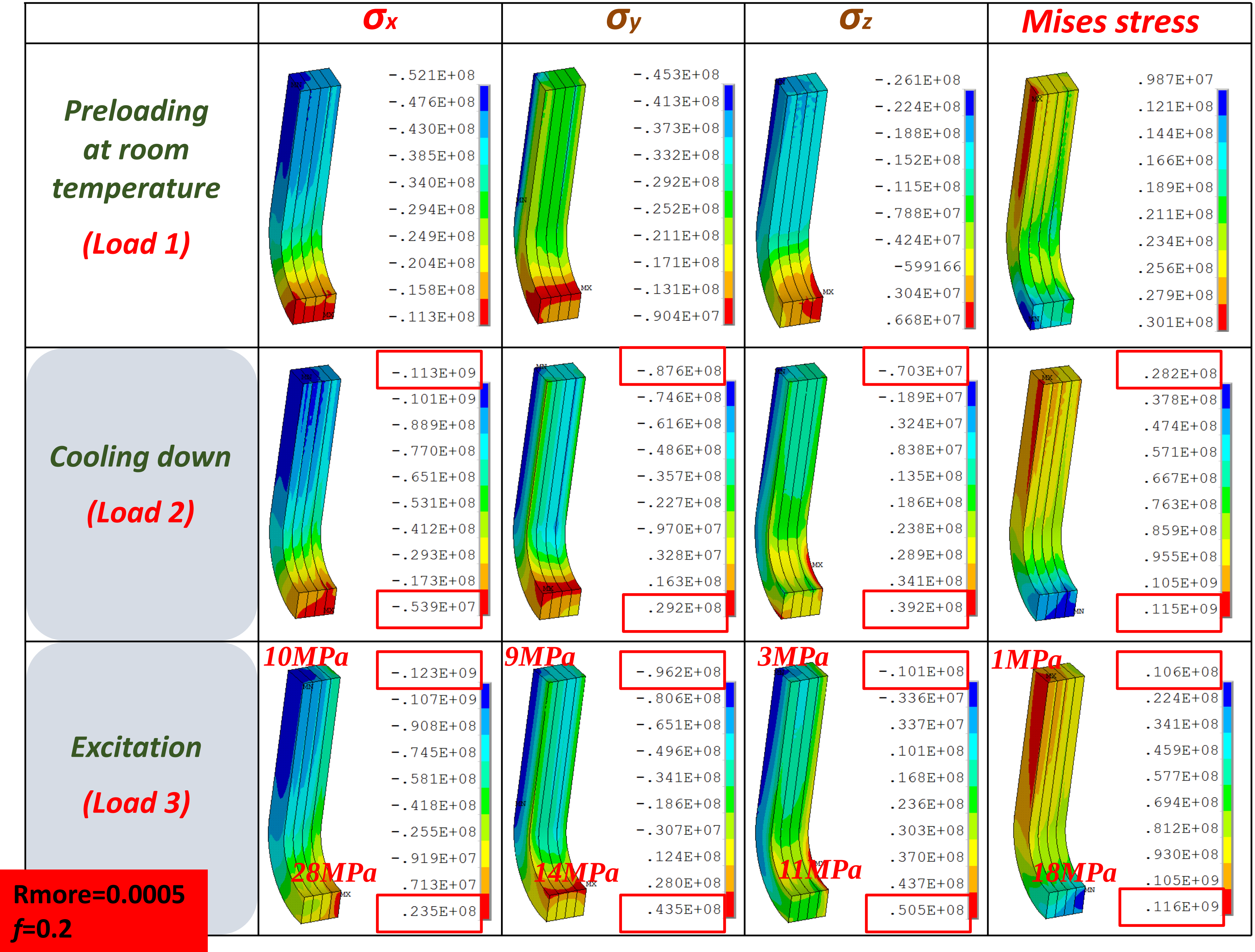
Main Design Parameters

Operating current	(A)	3970
Operating temperature	(K)	4.2
Operating field	(T)	12.01
Margin along the loadline	(%)	~18.4
Dipole diameter	(mm)	720
No. of Nb3Sn coils		2
No. of NbTi coils		2
No. turns of each Nb_3Sn coil		20*2
Cable size		5.8mm*1.5mm
Lorentz force Fx (per aperture)		760217 N
Lorentz force Fy (per aperture)		79972.3 N
Lorentz force FZ (per aperture)		41,769 N





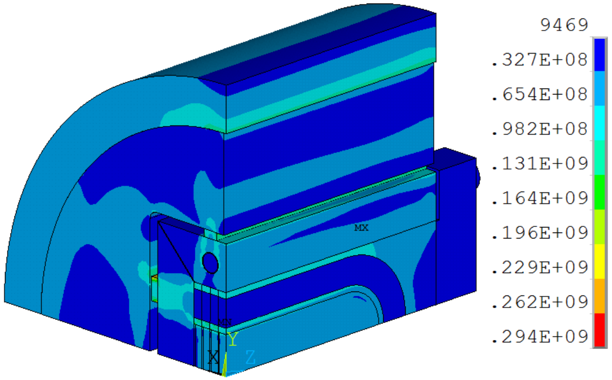



σx
σy
σz
Mises stress
Preloading at room temperature
(Load 1)
-.521E+08
-.476E+08
-.430E+08
-.385E+08
-.340E+08
-.294E+08
-.249E+08
-.204E+08
-.158E+08
-.113E+08
-.453E+08
-.413E+08
-.373E+08
-.332E+08
-.292E+08
-.252E+08
-.211E+08
-.171E+08
-.131E+08
-.904E+07
-.261E+08
-.224E+08
-.188E+08
-.152E+08
-.115E+08
-.788E+07
-.424E+07
-599166
.304E+07
.668E+07
.987E+07
.121E+08
.144E+08
.166E+08
.189E+08
.211E+08
.234E+08
.256E+08
.279E+08
.301E+08
Cooling down
(Load 2)
-.113E+09
-.101E+09
-.889E+08
-.770E+08
-.651E+08
-.531E+08
-.412E+08
-.293E+08
-.173E+08
-.539E+07
-.876E+08
-.746E+08
-.616E+08
-.486E+08
-.357E+08
-.227E+08
-.970E+07
.328E+07
.163E+08
.292E+08
-.703E+07
-.189E+07
.324E+07
.838E+07
.135E+08
.186E+08
.238E+08
.289E+08
.341E+08
.392E+08
.282E+08
.378E+08
.474E+08
.571E+08
.667E+08
.763E+08
.859E+08
.955E+08
.105E+09
.115E+09
Excitation
(Load 3)
10MPa
28MPa
-.123E+09
-.107E+09
-.908E+08
-.745E+08
-.581E+08
-.418E+08
-.255E+08
-.919E+07
.713E+07
.235E+08
9MPa
14MPa
-.962E+08
-.806E+08
-.651E+08
-.496E+08
-.341E+08
-.186E+08
-.307E+07
.124E+08
.280E+08
.435E+08
3MPa
11MPa
-.101E+08
-.336E+07
.337E+07
.101E+08
.168E+08
.236E+08
.303E+08
.370E+08
.437E+08
.505E+08
1MPa
18MPa
.106E+08
.224E+08
.341E+08
.459E+08
.577E+08
.694E+08
.812E+08
.930E+08
.105E+09
.116E+09
Rmore=0.0005
f=0.2

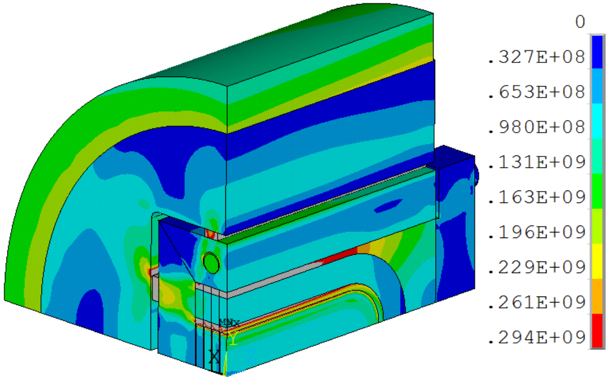
R&D Steps for 20T Dipole Magnet 2016-18

K. Zhang, C. Wang et al.

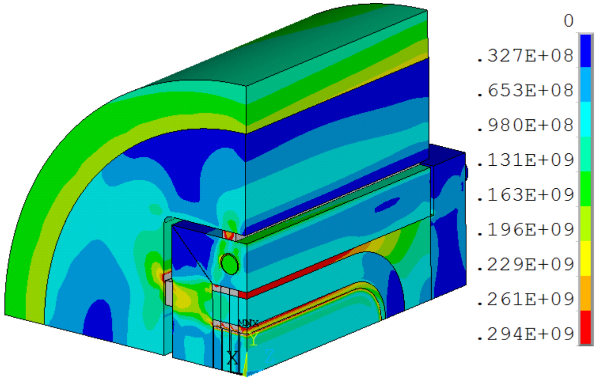
Mechanical analysis



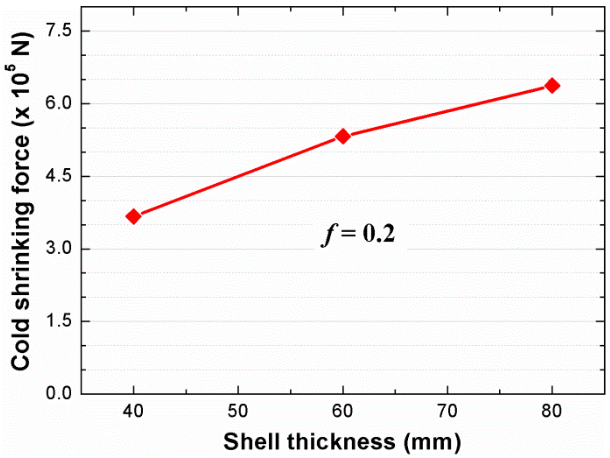
Von-mises stress after load 1 (interference analysis)



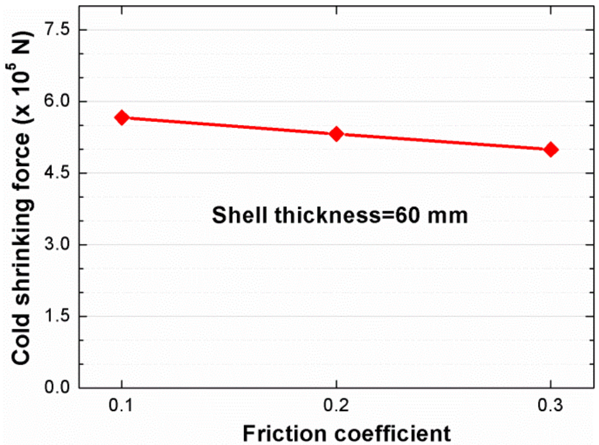
Von-mises stress after load 2 (cool down)



Von-mises stress after load 3 (excitation)



Rmore=0.0005; *f*=0.2

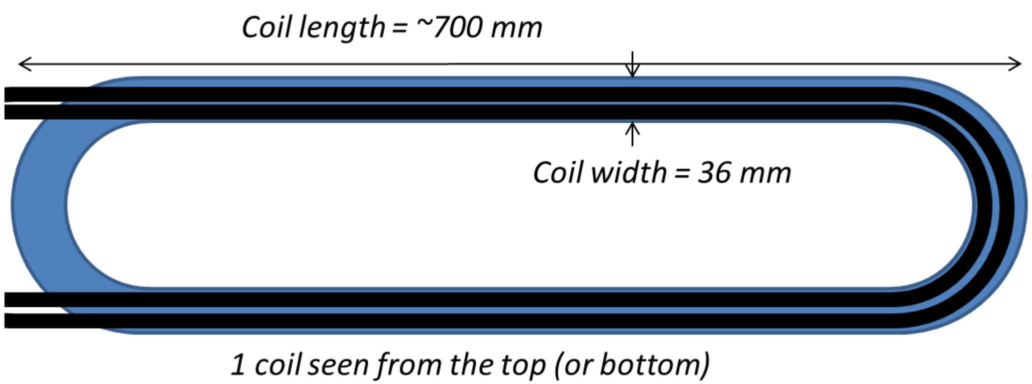


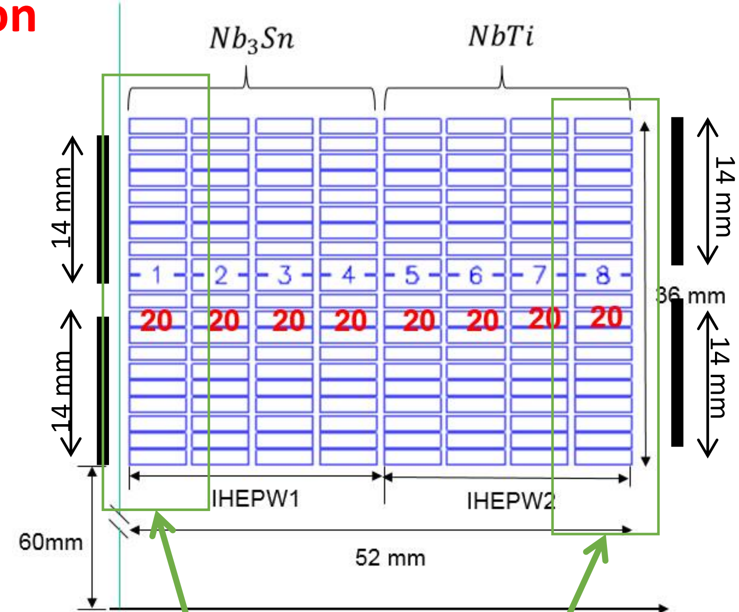
***Kai Zhang**, Chengtao Wang, Qingjin Xu, Zian Zhu, Yingzhe Wang, Da Cheng, Ershuai Kong, Feipeng Ning, Meifen Wang, Ling Zhao, Wei Zhao, and Quanling Peng, "Mechanical Design of FECD1 at IHEP: a 12-T Hybrid Common-coil Dipole Magnet" **2016 Applied Superconductivity Conference**. September. 2016*

R&D Steps for 20T Dipole Magnet 2016-18

T. Salmi (TUT), D. Cheng et al.

Quench protection



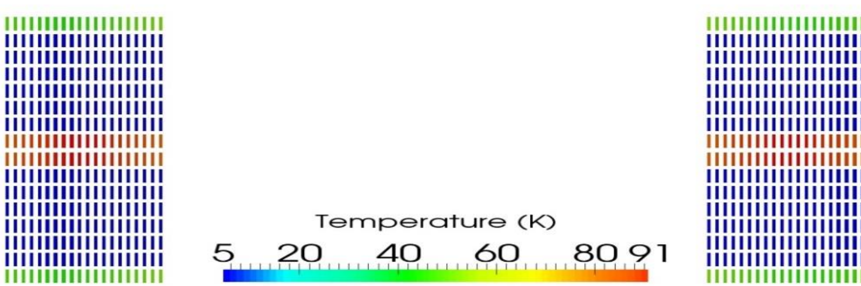


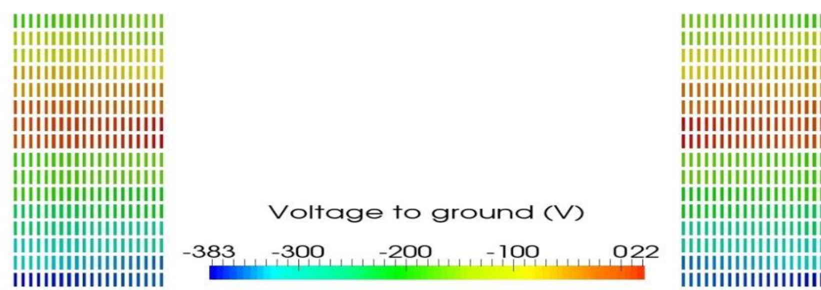
- 4 strips / coil, like in picture, each 14 mm wide
- 2 strips connected in parallel to 1 HFU – peak power 100 W/cm2 and tau = 30 ms
- Dump resistor with 90 mOhm
- **Detection delay = 20 ms** -> 20 ms after inital quench dump and haeters are activated

Heater delay for this layer = 10 ms

Heater delay for this layer = 20 ms

Other turns do not quench!



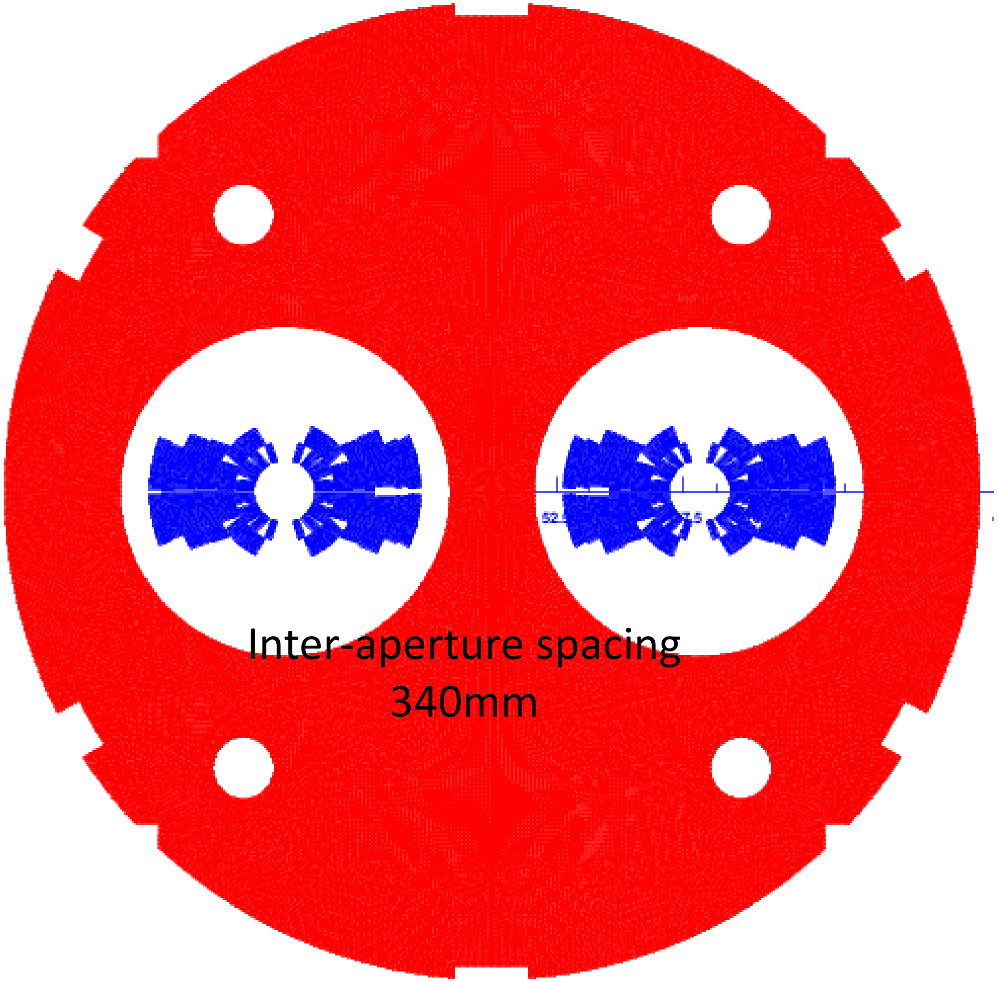


R&D Steps for 20T Dipole Magnet 2016-18

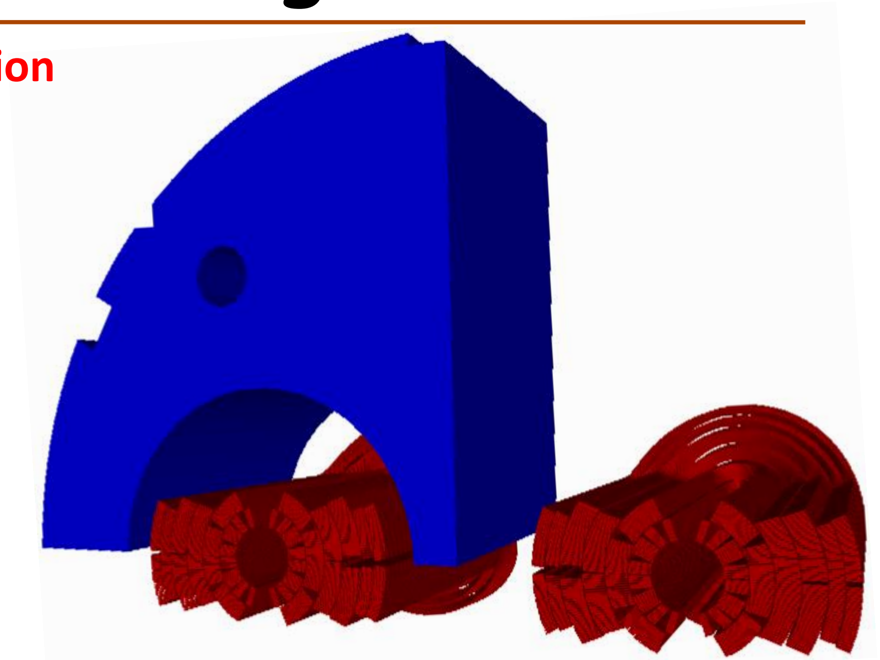
C. Wang et al.

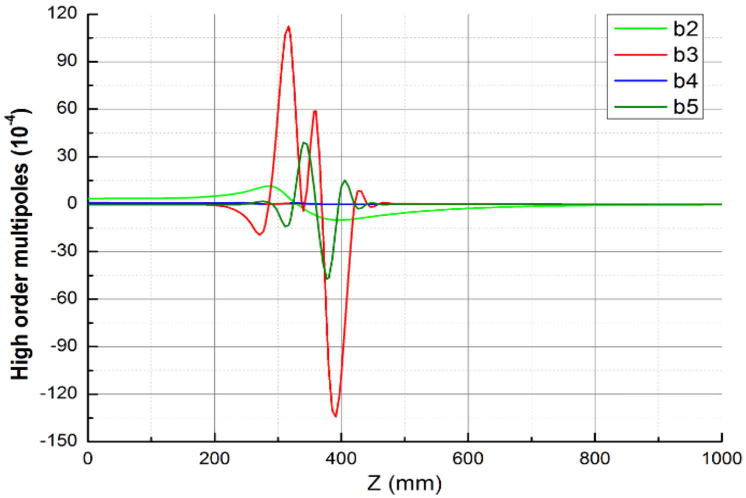
Cos-theta option

20-T cos-theta 2-in-1 dipole magnet with asymmetric coil configuration



Aperture 2* 50 mm; Iron OD 800mm





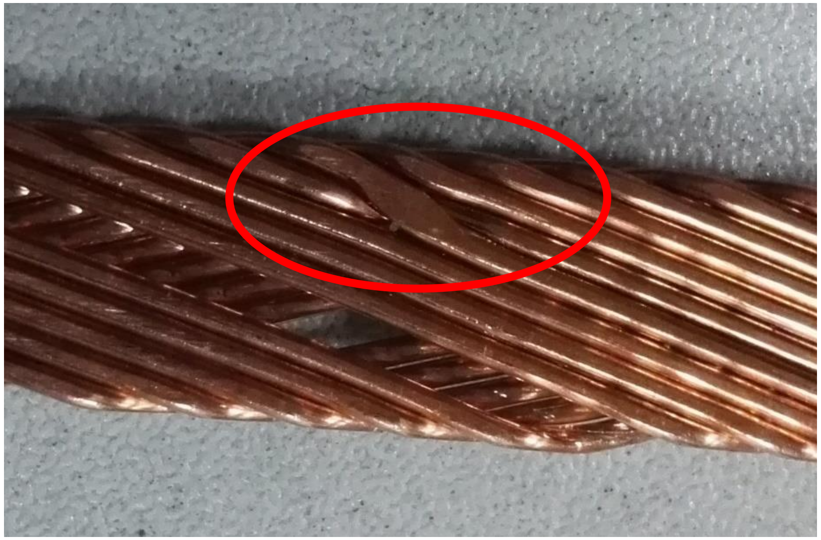
High-order harmonics along axis for the optimized coil ends (Rref = 17 mm)

Development Status: Rutherford Cable

Y Zhu, Y Li et al.

Reminder

Collaboration between WST, Toly Electric, Changtong Electric and IHEP



Superconducting Rutherford Cable fabricated by Toly Electric with WST Nb_3Sn strand

Superconducting Rutherford Cable fabricated by Changtong Electric with WST Nb_3Sn strand

Development Status: Rutherford Cable

Y Li et al.

Collaboration between WST, Toly Electric, Changtong Electric and IHEP

西部超导 11股*Φ0.70mm

11股*Φ0.74mm

Development Status: Rutherford Cable

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西部超导

11股卢瑟福缆性能对比

NbTi cables	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

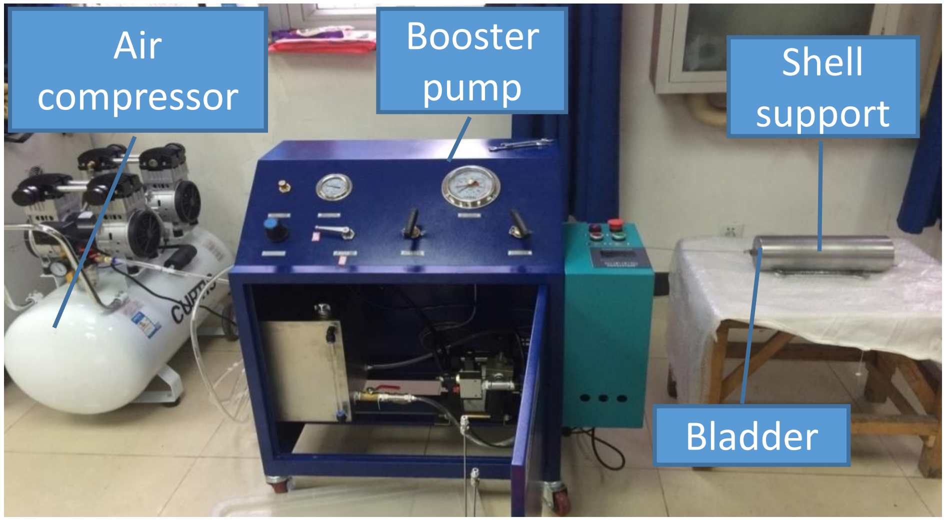
Fabrication and test of Nb_3Sn cables are ongoing

Development Status: Bladder

K. Zhang, C. Wang et al.

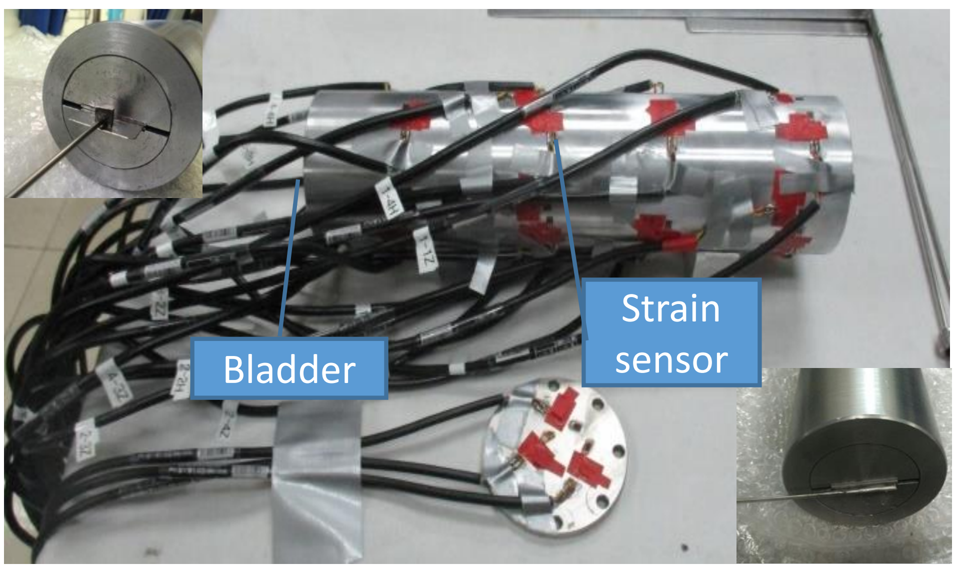
Reminder

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



Test results of bladder 001-004

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

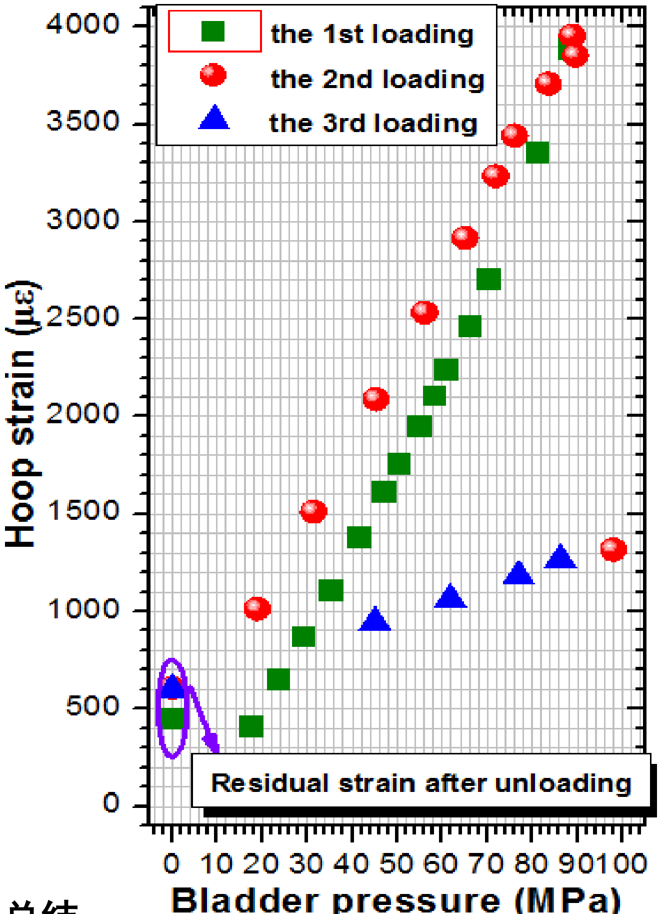


- **The present thickness of the shim and round tube is 0.3 mm.**
- **Leak always appear at the welding area between the shim and round tube.**
- **To increase the thickness of the shim and round tube to 0.5 mm for the new bladders.**

Development Status: Bladder

K. Zhang, C. Wang et al.

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



Reminder

18.9 MPa → 31.4 MPa → 45.3 MPa → 56.1 MPa → 65.1 MPa → 71.9 MPa → 76.1 MPa → 83.6 MPa → 88.9 MPa → 89.6 MPa → 98 Mpa → 0 MPa

第二次水压加载

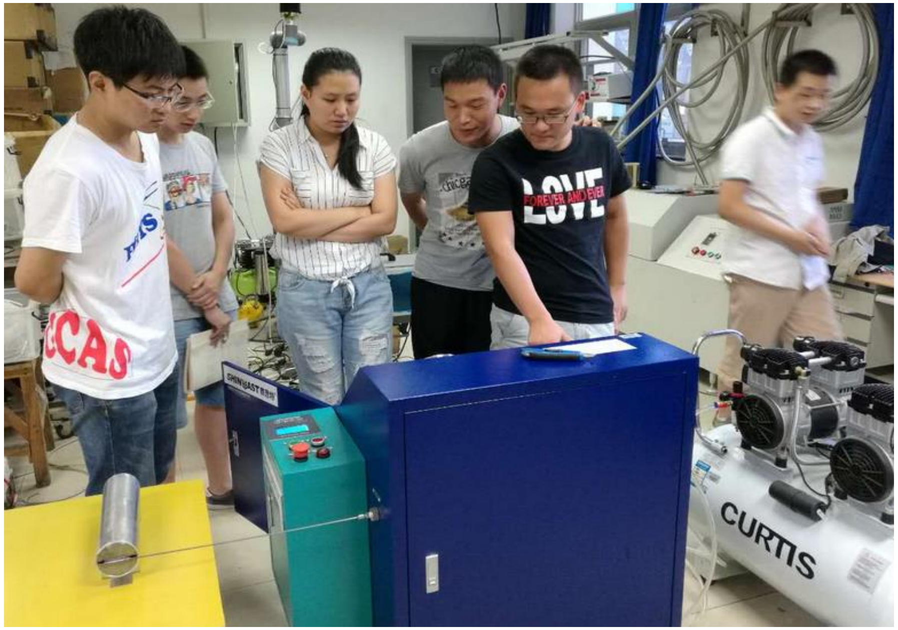
总结：

1) 第一次水压试验压力连续加载至88 MPa, bladder无泄漏、压力可以稳定维持、应变仪读数稳定；
2) 第二次水压试验压力连续加载至89.6 MPa, bladder无泄漏、压力可稳定维持，更改气泵的最大供气压力后，由于设置失误水压瞬间冲高至98 MPa, bladder发生泄漏，此后压力在泄漏的状况下可以稳定在96 Mpa左右；
3) 第三次水压试验是为了测试bladder在已经发生泄漏后的再次加载性能，可以发现bladder依然可以从零稳定加压至77 Mpa, 加载到86.3 Mpa后压力略有细微波动，但基本能保持住。

Development Status: Bladder

K. Zhang, C. Wang et al.

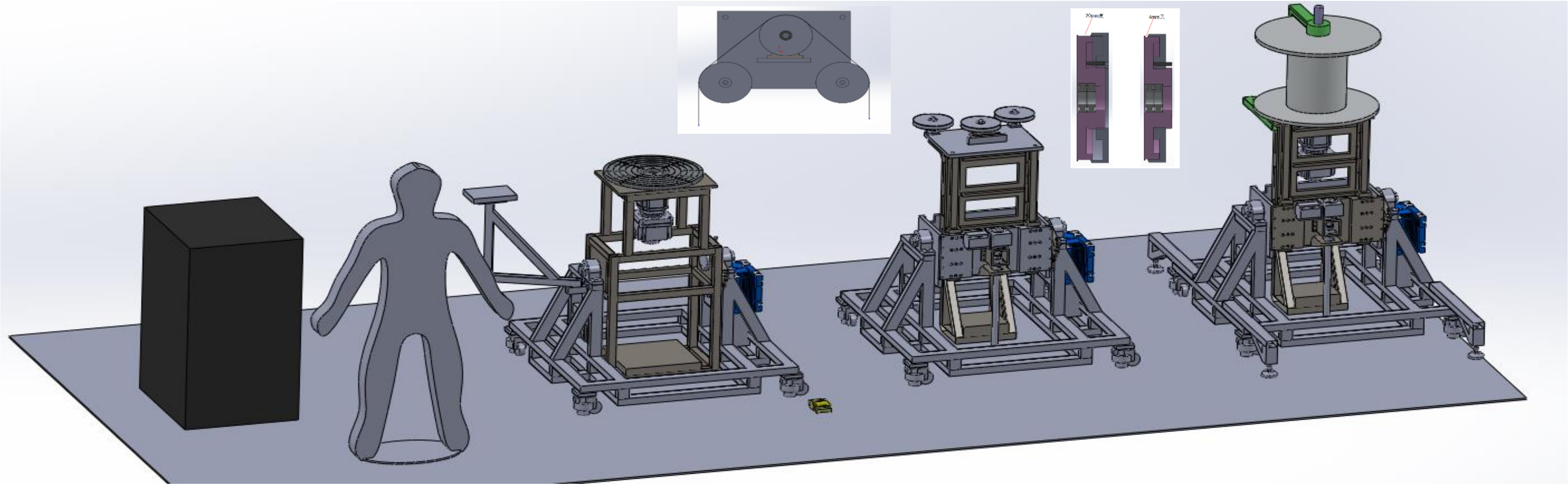
Latest progress: 102 Mpa achieved!!



Development Status: Winding Machine

Collaboration between SSTC and IHEP

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



National Collaboration

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

主办单位：中科院高能物理研究所

中国科学院高能物理研究所

协办单位：上海交通大学 中科院合肥物质科学研究所

上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

CASHIPS 中国科学院合肥物质科学研究院
Hefei Institutes of Physical Science, Chinese Academy of Sciences

承办单位：上海超导科技股份有限公司

上海超导科技股份有限公司
Shanghai Superconductor Technology Co., Ltd

International Collaboration

With LBNL: send students to Berkeley to work with US colleagues on the high field magnet R&D for SPPC, specially on Nb_3Sn and HTS magnet development.
1st student: Kai Zhang, depart to Berkeley next month and stay one year.

With BNL: send young staff to Brookhaven to work with US colleagues on the high field magnet R&D for SPPC, Specially on HTS coil development.
1st staff: Qing Li, depart to Brookhaven this month and stay 2 months.

With CERN: Visit CERN next month with WST and IPP colleagues to discuss the possibility of participating the HL-LHC project, fabricating high field magnets and current leads for HL-LHC.

With TUT (Finland): Setting up formal collaboration between two sides on advanced quench protection methods for high field magnets. Tiina Salmi visited IHEP last month (Aug. 14-27)

Next steps

- **Development of the 12~15T model magnets**
  - R&D and production of High J_c Nb_3Sn and HTS conductors
  - Cabling of Nb_3Sn and HTS conductors
  - Coil fabrication (winding, heat reaction, impregnation, joints)
  - Quench protection of the Nb_3Sn and HTS coils
  - Field quality optimization of the HTS dipole magnets
  - Mechanical analysis and support structure assembly
  - Cold test of the magnets (magnetic field, field quality, quench behavior)

- **Advanced HTS conductors R&D and quality evaluation**
  - R&D of high-J_c & Low-cost HTS superconductors: Iron-based, ReBCO and Bi-2212)
  - Quality evaluation of the HTS superconductors: Jc, mechanical and dynamic behaviors, model coil fabrication and test with high background field

Thanks