Recent Progress of Large Scale Application in China-A Review

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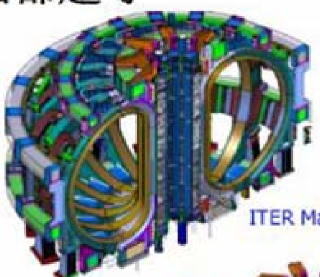
Content

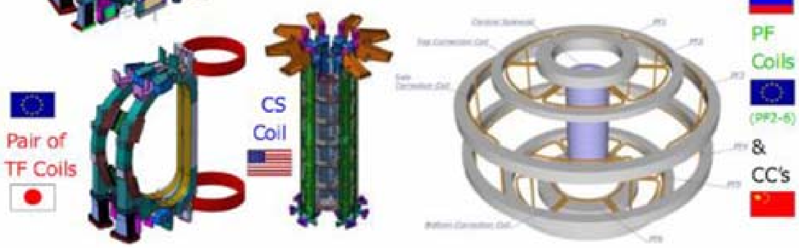
- Materials for Large-Scale Application;
- Power Applications;
- Superconducting Magnet;
- Maglev;

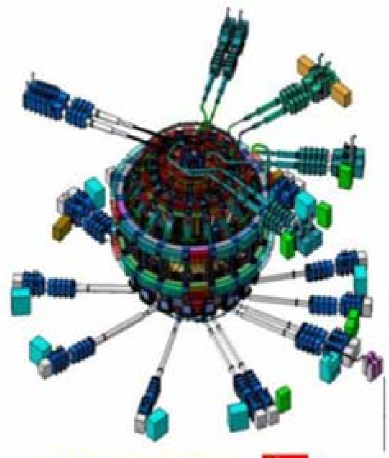
西部超导

Superconducting Strands for ITER



- The ITER magnet system is made up of
  - 18 Toroidal Field (TF) Coils,
  - a 6-module Central Solenoid (CS),
  - 6 Poloidal Field (PF) Coils,
  - 9 pairs of Correction Coils (CC's).

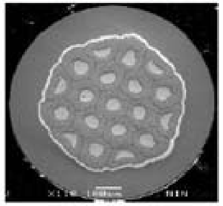




China (WST):

174 t NbTi strand

35 t Nb_3Sn strand



Coils	Superconducting wire	Weight (t)	Proportion (%)					
			CN	EU	JA	KO	RF	US
TF	Nb_3Sn	420	7.5	20.2	25	20	19.3	7.8
CS	Nb_3Sn	122			100			
PF	NbTi	224	65				35	
CC/Feeder	NbTi	21	100					

西部超导

Workshop of Superconducting strand for MRI

- New workshop and production lines were established in 2013, especially for MRI strand production.
- Capability of MRI strand is over 500 ton per year.

西部超导

NbTi/Cu Superconducting Wires for MRI

- WST can design and produce monolith and WIC strand for MRI customers all over the world.

NbTi SUPERCONDUCTING WIRE(Wire in channel)

	Nominal Dimension(mm)		Number of filaments	Filament Diameter (μm)	Nominal Cu/non-Cu	Critical Current (Amps @4.2K)			n value	Insulation	RRR (300K/10K)
	Bare	Insulated				2T	3T	4T			
1	3.120 × 1.680	3.390 × 1.950	55	77	19	>700	>560	>500	>40(4T)	PET	>175
2	2.670 × 1.320	2.940 × 1.590		68	15.9	>560 (2.5T)	>450	>400			
3	2.700 × 1.340	2.940 × 1.590		82	11	>1530	>1210	>1000	>30(3T)		
4	2.286 × 1.524	2.553 × 1.765		93	7.7	>2000	>1550	>1210			
5	2.286 × 1.524	2.553 × 1.765		82	10.5	>1490	>1210	>950			
6	1.978 × 1.173	2.240 × 1.425		83	6.6	>1350	>1080	>1000	>40(4T)		
7	1.978 × 1.173	2.240 × 1.425		79	7.5	>1230	>980	>875			
8	1.978 × 1.173	2.240 × 1.425		75	7.8	>1130	>900	>780			
9	1.978 × 1.173	2.240 × 1.425		68	9.7	>930	>740	>600			
10	1.970 × 1.155	2.240 × 1.425		68	10.1	>560 (2.5T)	>450	>400			
11	1.680 × 1.100	1.950 × 1.370		68	8.3	>560 (2.5T)	>450	>400			
12	1.565 × 1.040	1.815 × 1.290		98	5	>1200	>960	>900			

NbTi SUPERCONDUCTING WIRE(Monolith, Rectangle)

	Number of filaments	Filament Diameter (μm)	Nominal Cu/non-Cu	Nominal Diameter(mm)		Critical Current (Amps @4.2K)						Insulation	RRR (273K/10K)
				Bare	Insulated	4T	5T	6T	7T	8T	9T		
1	18	83.5	10	1.47 × 0.77	1.55 × 0.85	>280	>245	>180	>135	>82	/	Formvar	>100
2	24	110	7	1.70 × 1.10	1.80 × 1.20	>630	>550	>420	>310	>190	>90		
3	36	52	4	0.80 × 0.50	0.85 × 0.55	>135	>120	/	/	/	/		
4		78	4	1.20 × 0.75	1.28 × 0.83	>500	>420	>325	>230	>145	>66		
5		112	4	1.70 × 1.10	1.80 × 1.20	>1040	>870	>650	>495	>310	>145		
6	54	77	1.3	1.00 × 0.60	1.08 × 0.68	>710	>600	>468	>328	>205	>98		
7		94	1.3	1.20 × 0.75	1.28 × 0.83	>1045	>895	>685	>535	>325	>150		
8	630	22	1.3	1.00 × 0.60	1.10 × 0.70	>710	>600	>470	>330	>210	>100		
9		27	1.3	1.20 × 0.75	1.28 × 0.83	>1050	>900	>690	>540	>330	>155		
10		34	1.3	1.463 × 0.952	1.533 × 1.022	/	>1400	>1060	>800	>490	>235		
11		28	1.3	1.248 × 0.768	1.308 × 0.828	>1130	>960	>730	>530	>330	>150		

MRI system

GE

SIEMENS

UNITED IMAGING 联影

PHILIPS

MRI Magnet

健信 JIANXIN

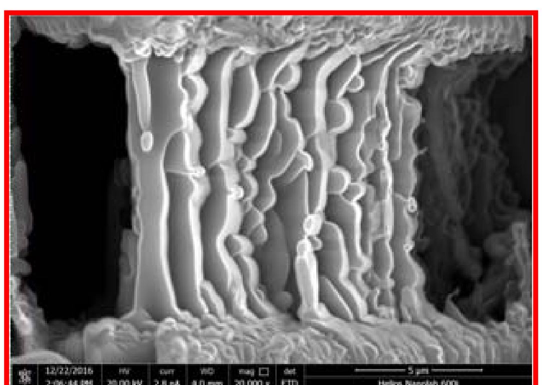
上海辰光医疗科技股份有限公司

JASTEC SUPERCONDUCTOR

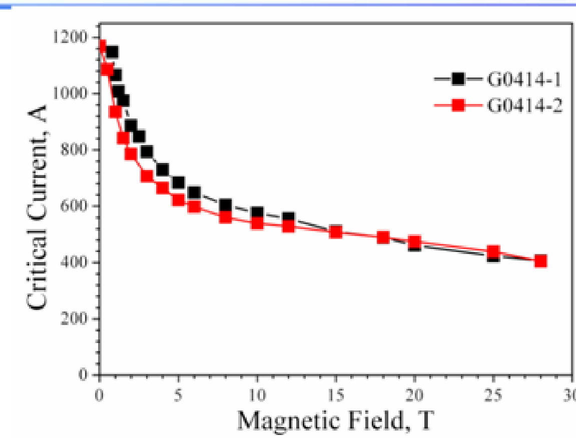
MITSUBISHI ELECTRIC

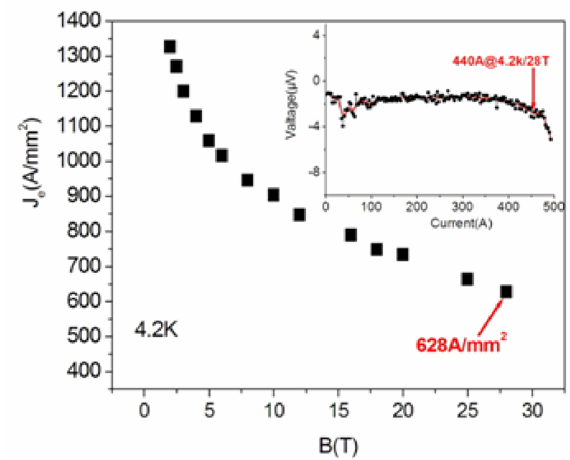
WST: Overpressure heat treatment for Bi-2212 wires

Pressure: 50-100atm
Temperature:900 ℃



High density filaments without pores
Clean grain boundaries

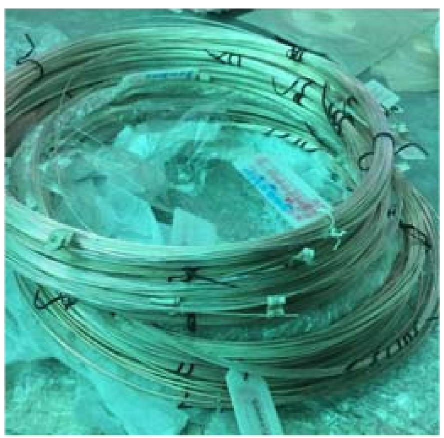




4.2K，28T: *Ic*~440A
***Jc*~3.1×10⁵A/cm2，*Jce*~6.2×10⁴A/cm2**

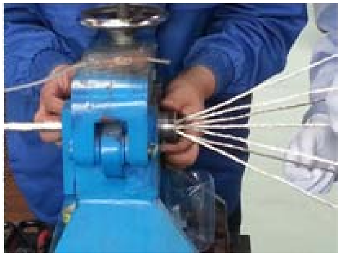
WST: Small batch of Bi-2212 wires production

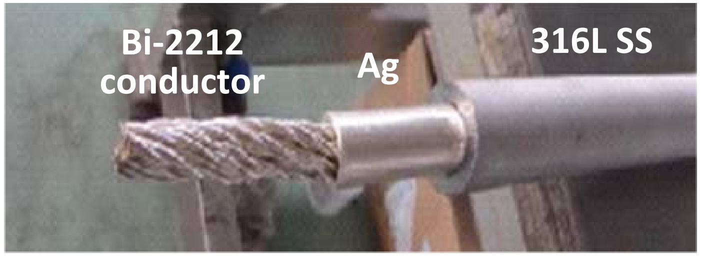


◆ **Industrial fabrication technique has been developed.**

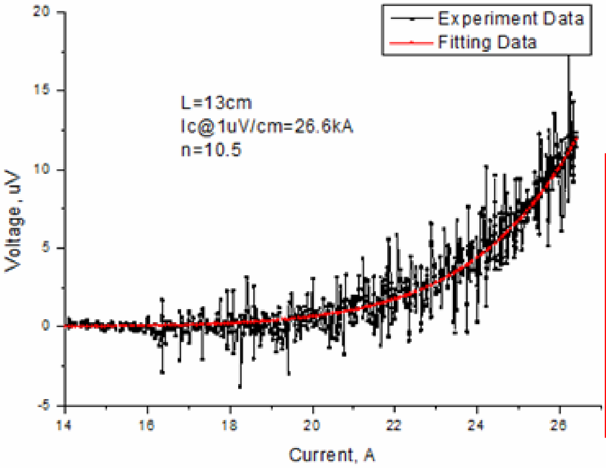
WST: Bi-2212 CICC conductor





Wires	Diameter	1.0mm
	Max. Tension stress	15%
	Strength	140N
First assembly	Number	2
	Tension	20N
	Pitch	18-20mm
Second assembly	Number	3
	Tension	20N
	Pitch	49mm
	Rotation speed	100r/min
Tertiary assembly	Number	7
	Tension	30N
	Pitch	90mm
	Rotation speed	50r/min

Joint resistivity: 4 nΩ, *I*c=26.6 kA@4.2 K



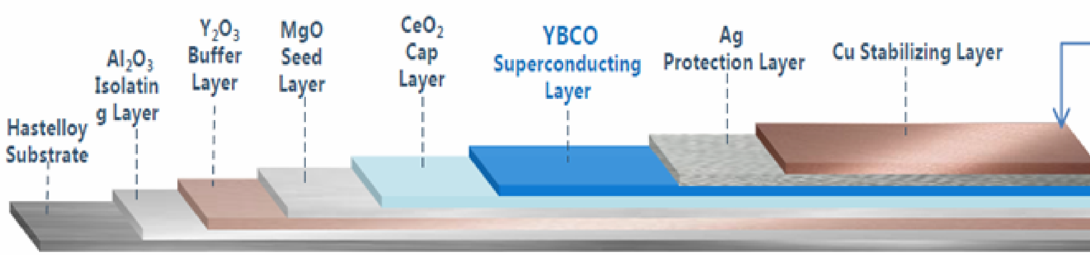
Bi-2212 cables fabricated with 42 Bi-2212 wires by cooperating with ASIPP

Main Groups and Techniques for 2G HTS Tapes in China

	Research Groups & Industry Partners	Buffer Layer		HTS Layer		
		textured NiW	untextured tape via IBAD	MOCVD	PLD	MOD
R&D	Tsinghua Uni.	√	√			√
	Beijing Tech. Uni.	√				√
	Northwest INM	√				√
	Southwest Jiaotong Uni.	√				√
	IEE CAS					√
	Uni. Electr. Sci.Tech	**R2R**	**√**	**√**		
	Beijing GRINM	**R2R**			**R2R**	
R & D/ Industry	**Suzhou Advanced Materials(SAMRI)**		**R2R**	**R2R**		
	Shanghai Superconductor		**R2R**		**R2R**	
	Shanghai Creative Superconductor		**R2R**		√	**R2R**

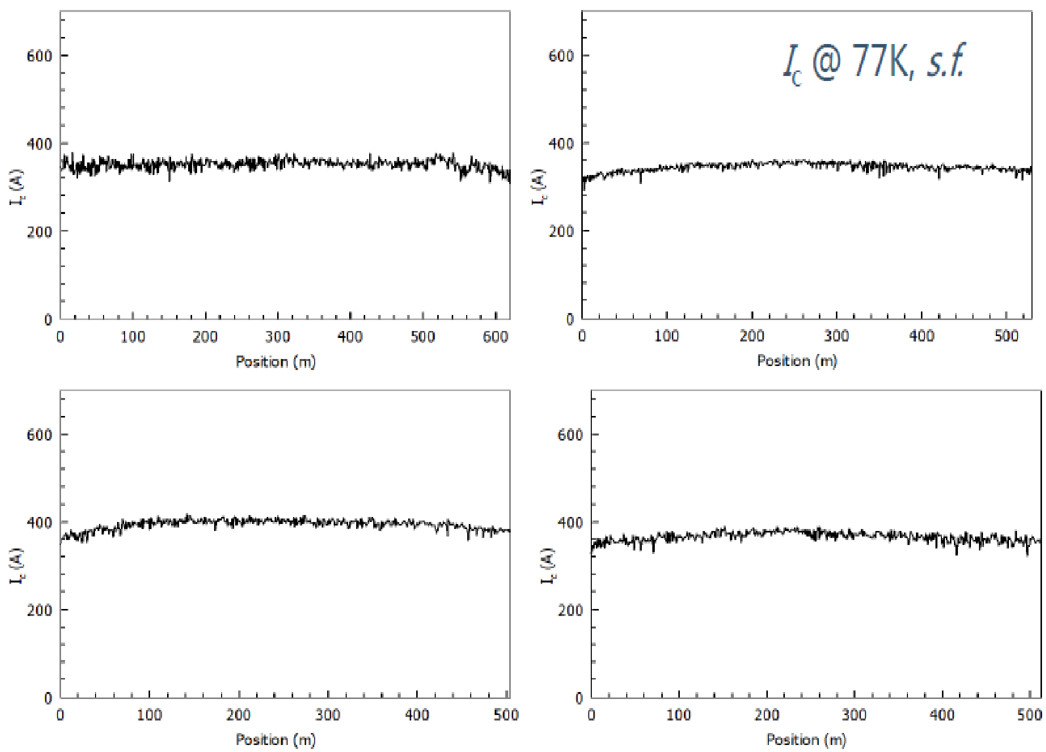
Shanghai Superconductor: YBCO, IBAD+PLD

Hastelloy Tape → Polishing | R2R RF Magnetron Sputtering | R2R IBAD | R2R HTRF Magnetron Sputtering | R2R PLD | R2R DC Magnetron Sputtering | Slitting Machine | Continuous Electroplating | Continuous Lamination → CC Tape

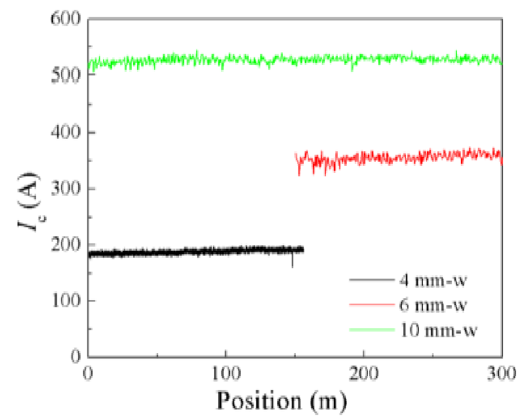


Shanghai Superconductor: ReBCO, Mass Production

before 2018



recently (2018) in optimized deposition process



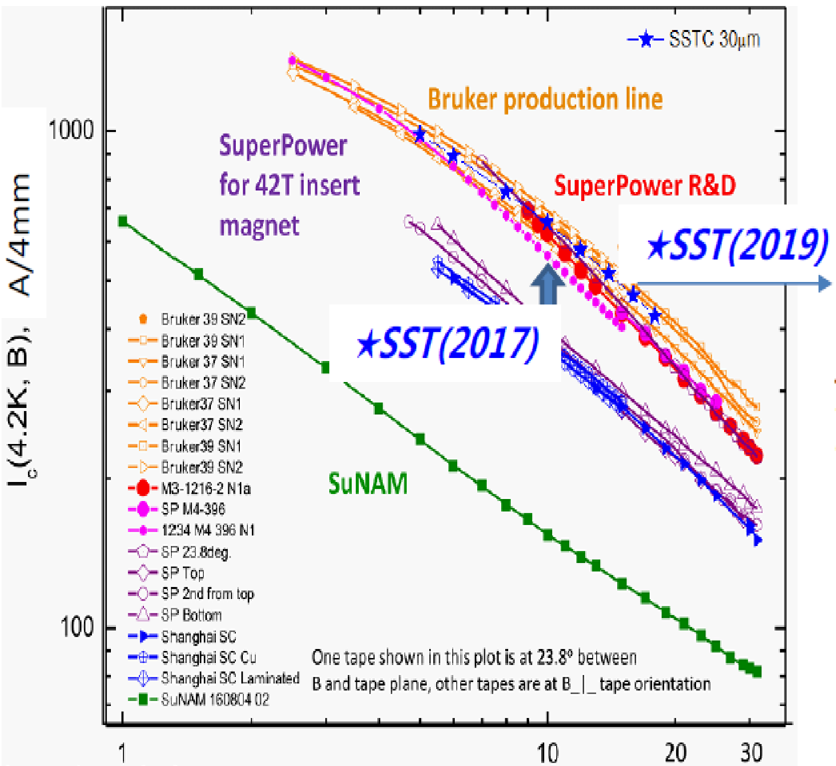
- Stable long tape production of 300-500 m piece length
- Production rate is doubled while achieving high I_c

9

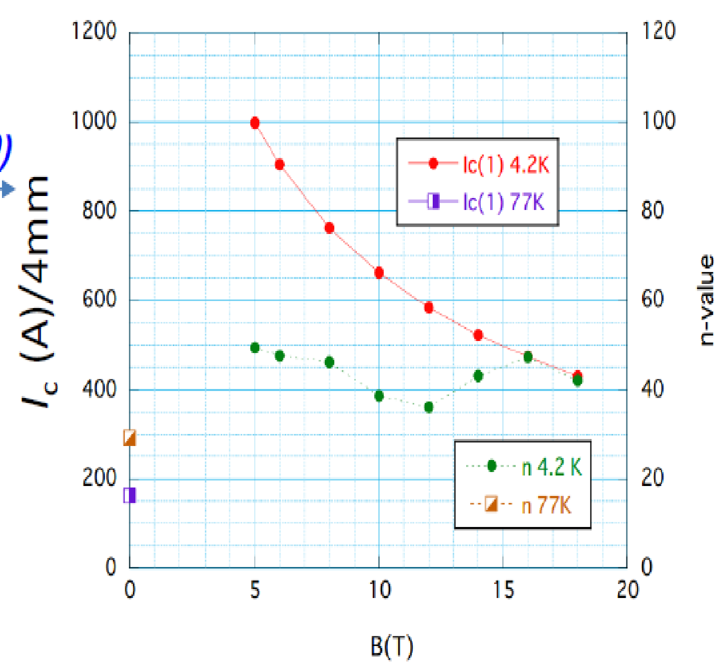
Shanghai Superconductor: ReBCO @ 4.2K and High Field

I_c increased

- R&D sample (2018)
- Mass production (2019)



last EUCAS 2017



Measured byKEK

Suzhou Adanced Materials: YBCO, IBAD+MOCVD

A: Lamination (Copper, Stainless Steel), 20~175μm

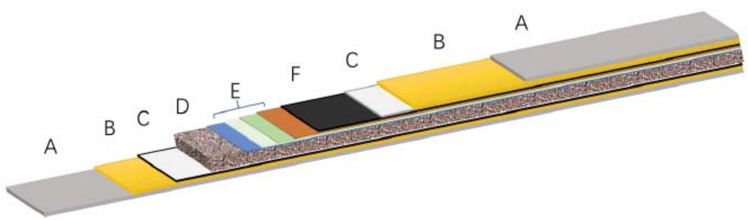
B: Copper:2~5um

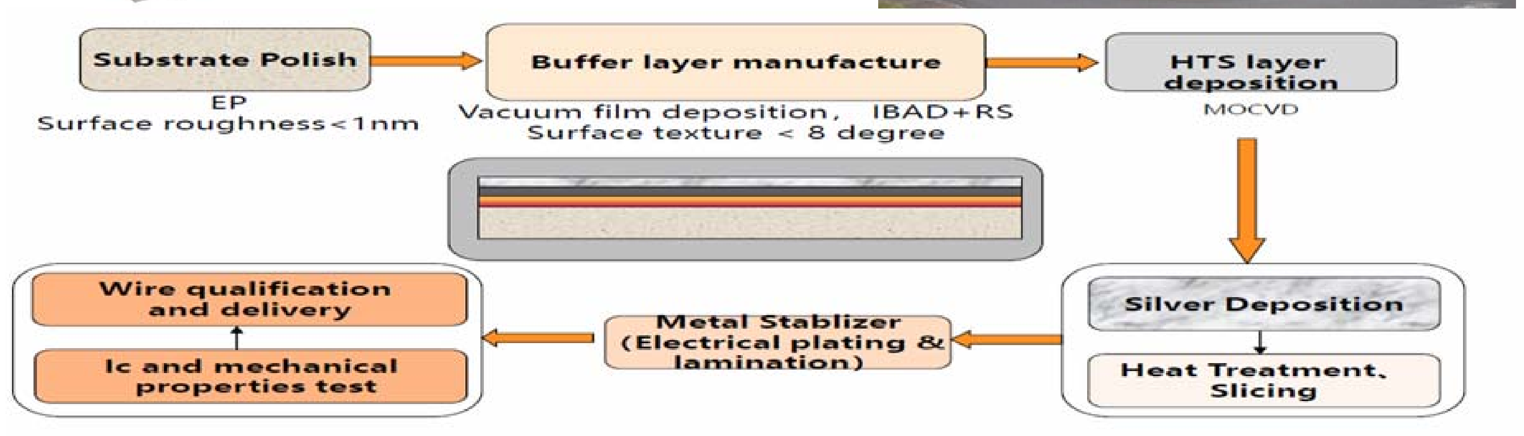
C:Silver ~2um

D: Substrate: 50~65μm Hastelloy

E: Buffer Layer 0.2μm

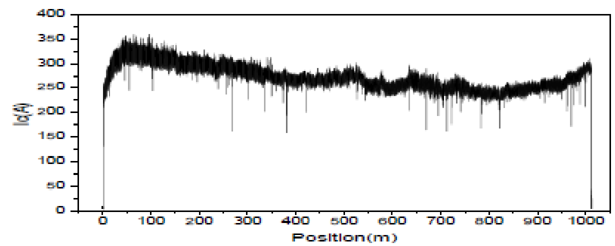
F: ReBCO: ~2μm



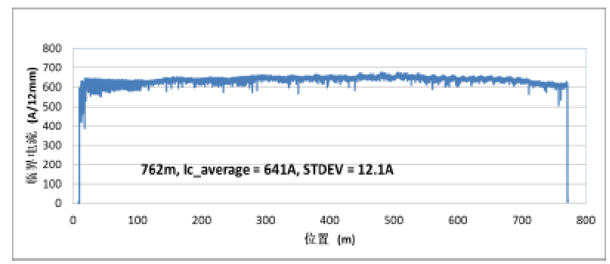


Suzhou Adanced Materials: YBCO, IBAD+MOCVD

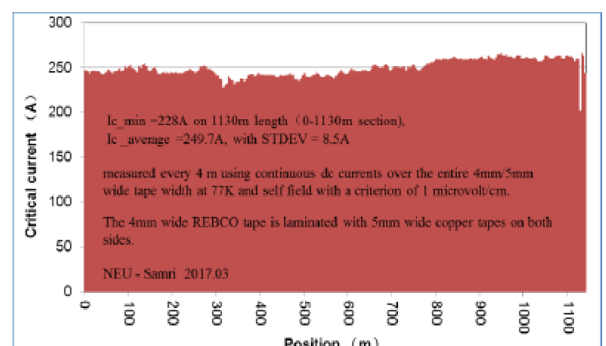
In December 2014 **1012**m Ic(77K,sf) =**273**A/12mm



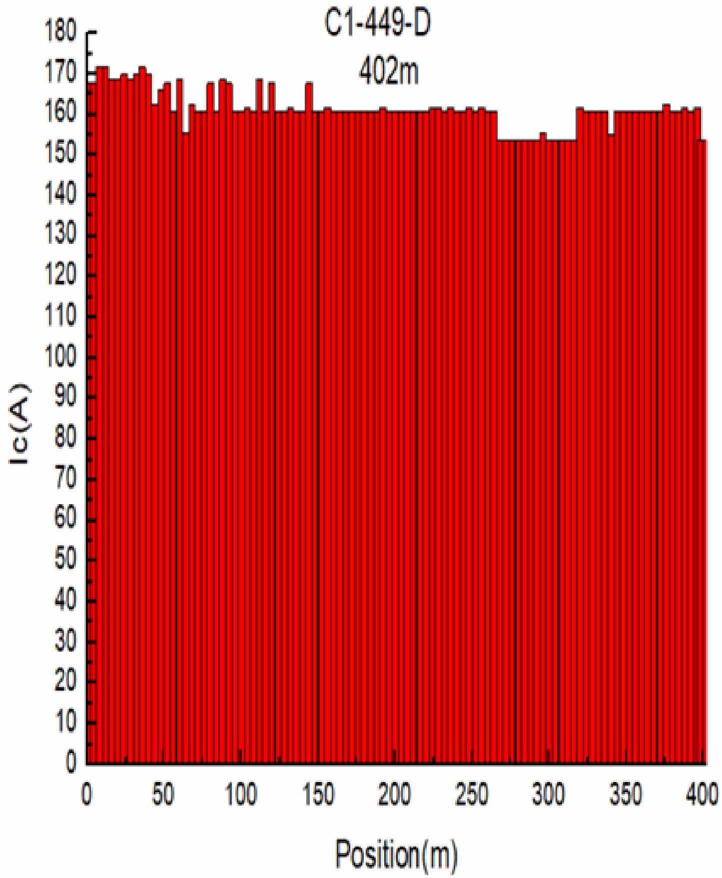
In January 2016 **762**m Ic(77K,sf) = **641**A/12mm，The standard deviation**12.1**A/12mm



In March 2017 **1130**m Ic(77K,sf) =**249.7**A/4mm，COV≤ 3.6%



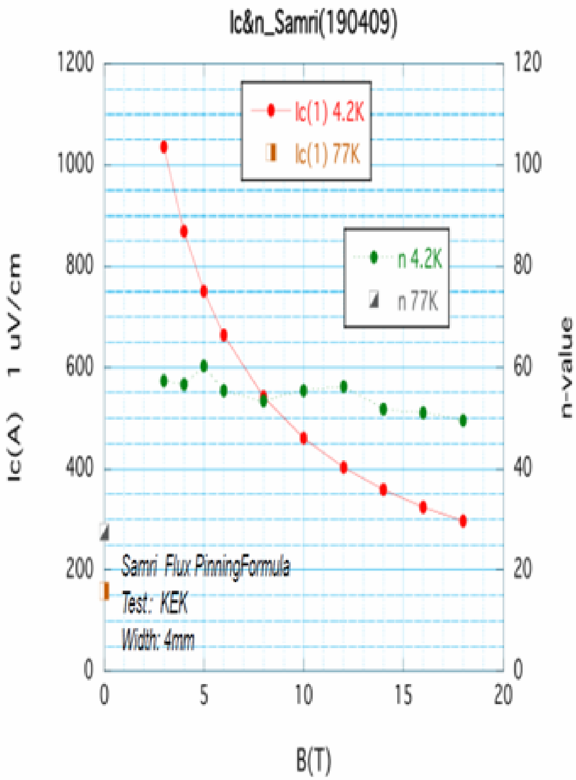
Suzhou Adanced Materials: YBCO, IBAD+MOCVD



Average:161A for 4mm tape, STDEV: 4.57A, COV: 2.8%
Production date: Jan 2019

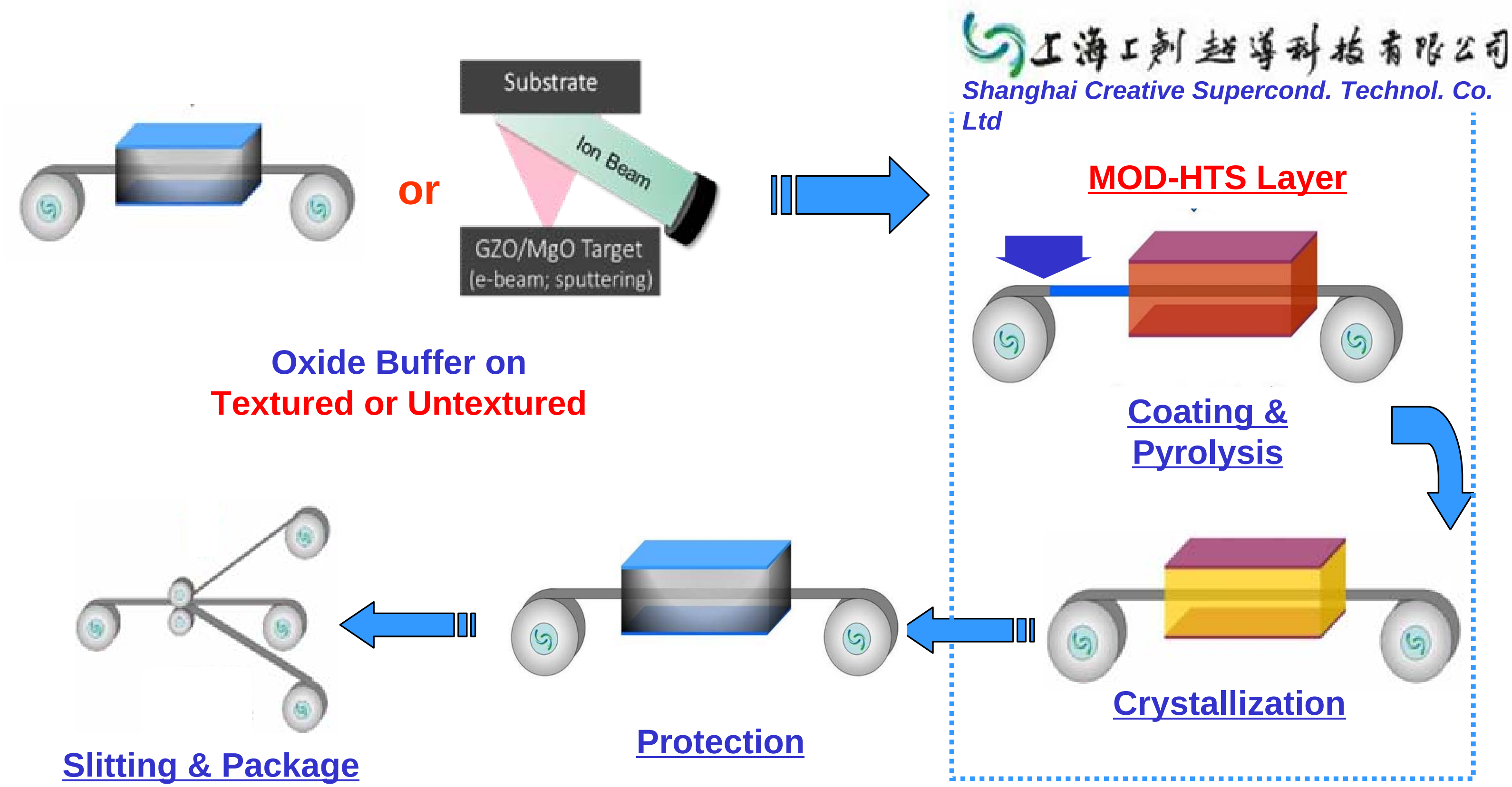
Commercial REBCO wire Ic value at 4.2K, tested in April 2019

K. Tsuchiya @ High Energy Accelerator Research Organization (KEK Japan)

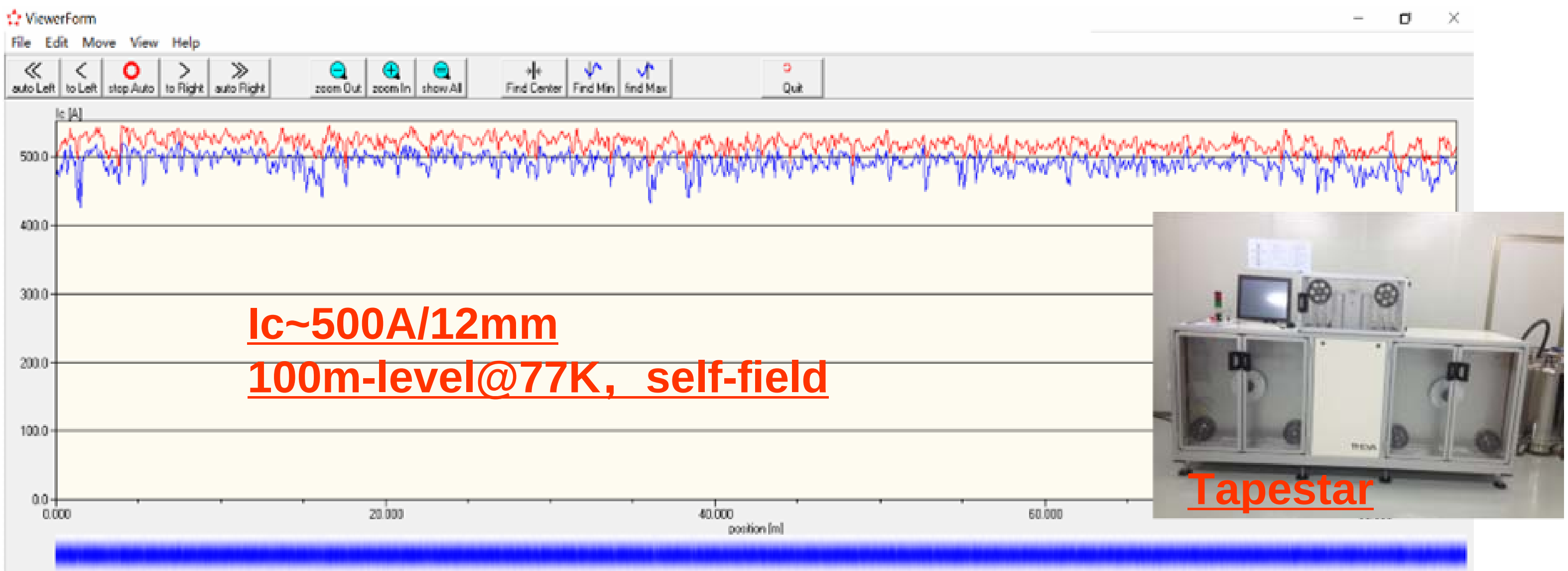


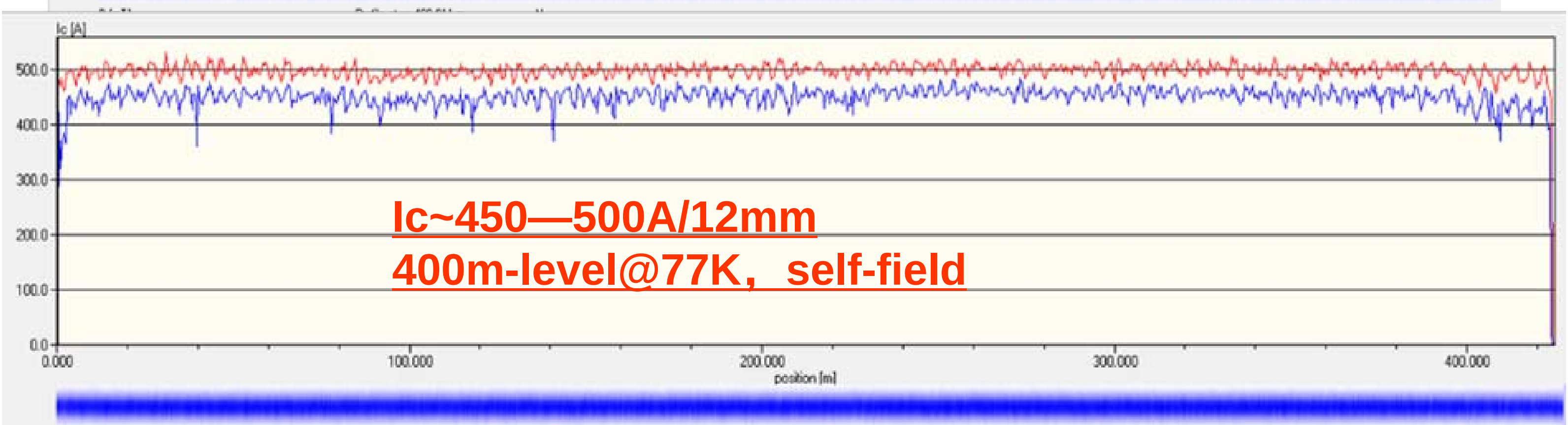
Shanghai Creative Superconductor: RABiTS or IBAD+MOD

- Textured Oxide Buffers on Textured or Untextured Tape via RABiTS or IBAD
- Epitaxial HTS Films on Textured Oxide Buffer via MOD

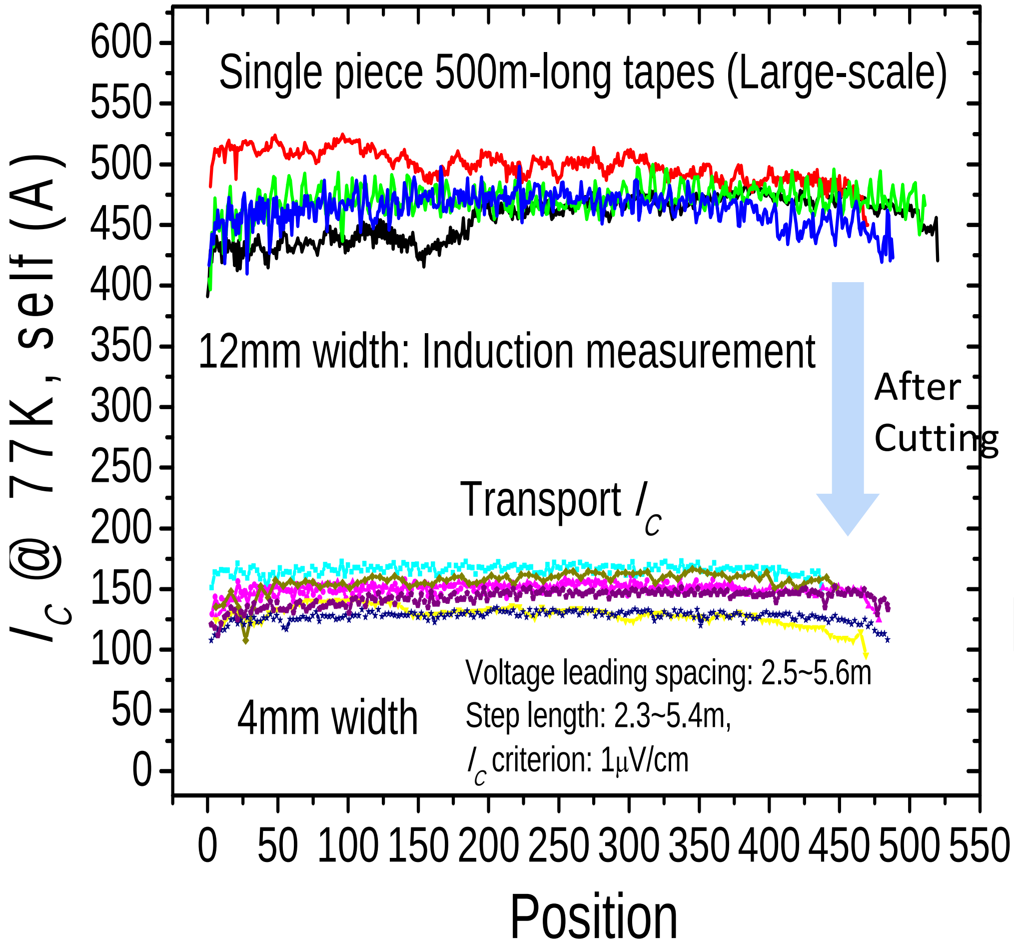


Critical Current for Modified MOD-HTS Tapes

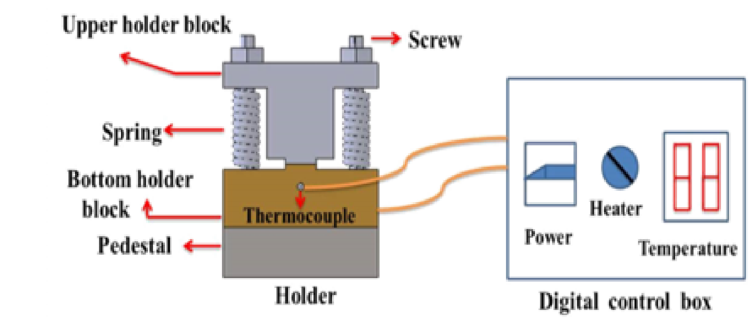


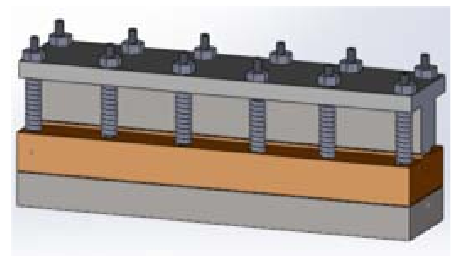


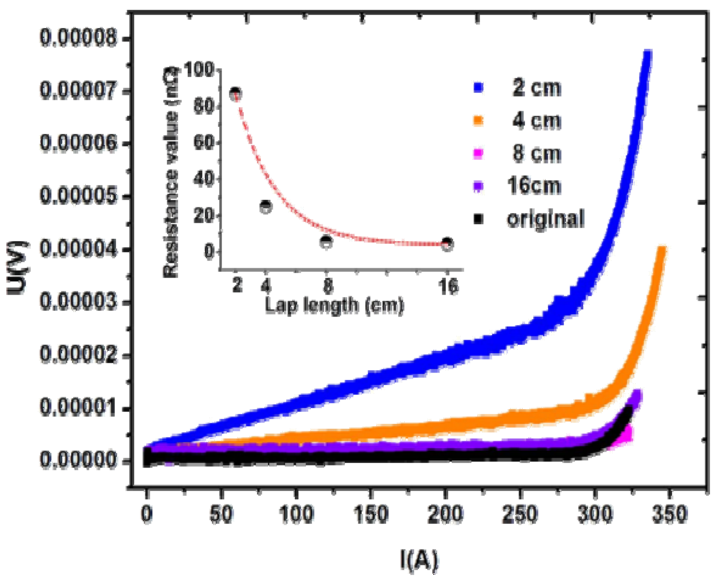
Typical performances for 12mm/4mm-wide products

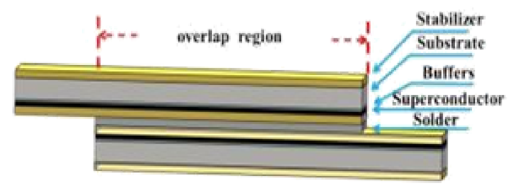


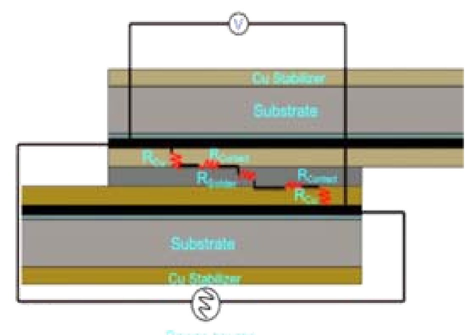
Joint Technology at Shanghai Creative











IEE—Iron Based PIT $Ba_{0.6}K_{0.4}Fe_2As_2$/Ag122 tapes

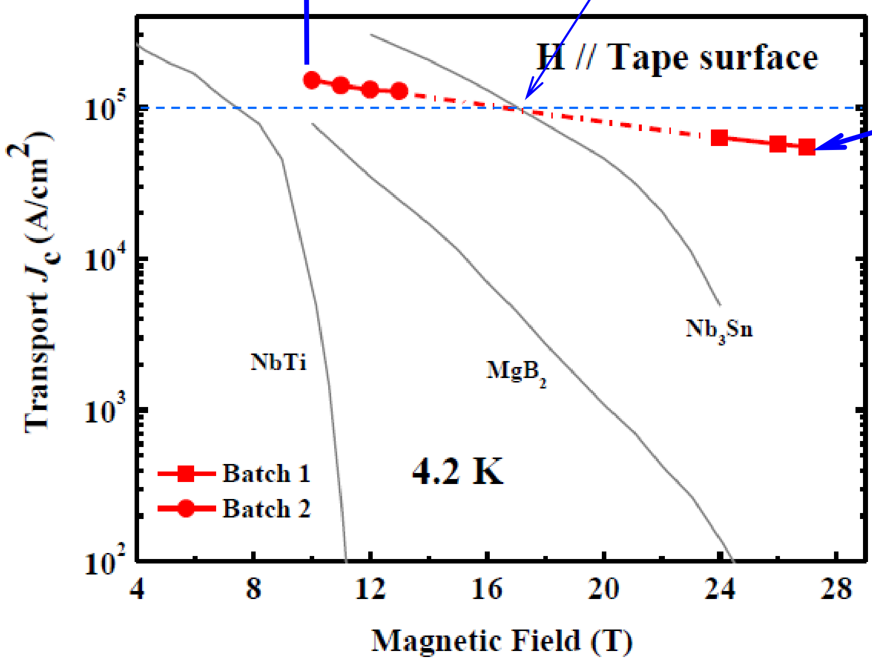
New record transport J_c up to 1.5×10^5 A/cm² @ 4.2 K, 10 T was achieved

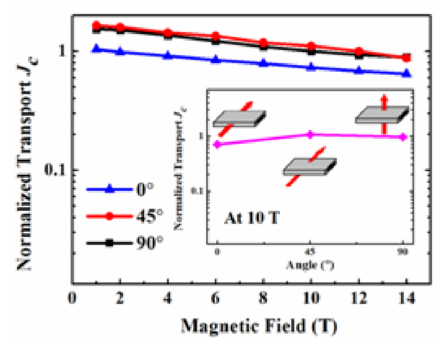
(~4 mm wide, 0.3 mm thick, short samples)

***I_c* = 437 A**

At 18 T, J_c = ~10^5 A/cm²

At 27 T, $J_c = 5.5\times10^4$ A/cm²



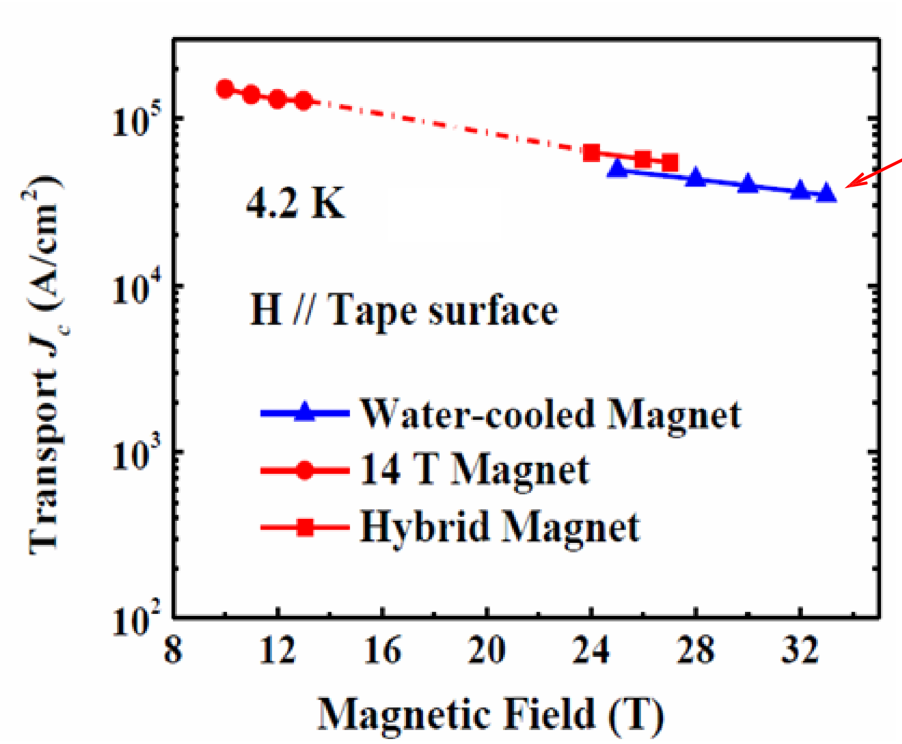


γ = 1.37 at 10 T

Huang et al., *SuST* 31 (2018) 015017

Ic measured in high fields up to 33 T at Hefei High Field Maglab

PIT $Ba_{0.6}K_{0.4}Fe_2As_2$/Ag122 tapes

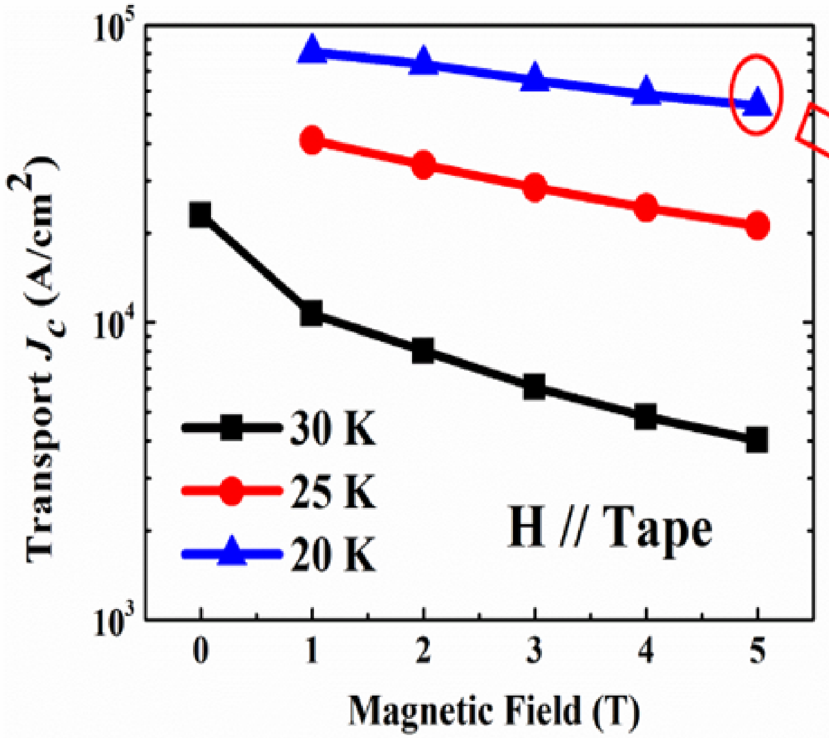


@ 33 T, Jc= 3.5 × 10^4 A/cm^2

Transport J_c at medium temperatures

-- HPed $Ba_{0.6}K_{0.4}Fe_2As_2$ /Ag tapes

Measured at Northeastern University in China



5.4×10^4 A/cm^2
@ 5 T & 20 K

Huang et al., ***SuST*** 31 (2018) 015017

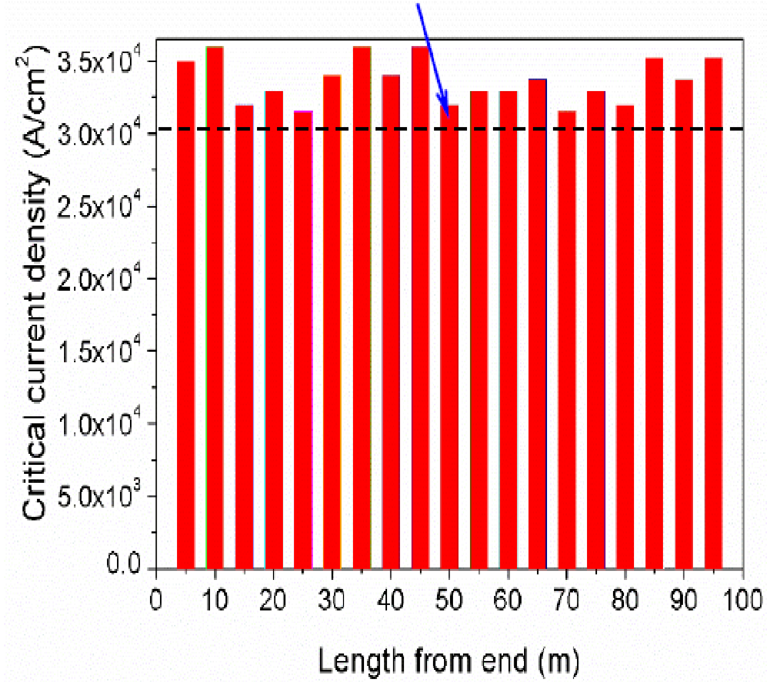
Strong potential for applications working at medium temperature region by cryogenic cooling systems.

Recently, transport J_c of 100 m long tapes was further enhanced: >30000 A/cm^2 (4.2 K, 10 T)

3 times larger than the first!

Key steps to the application

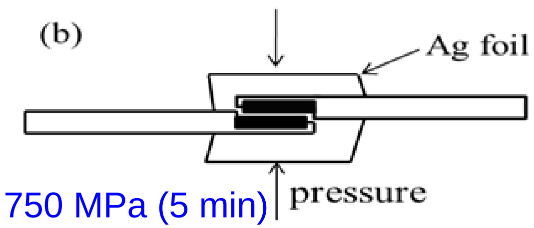
@4.2K, 10T, transport J_c >30000 A/cm^2

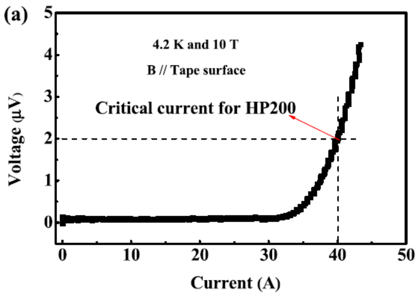


Supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB25000000).

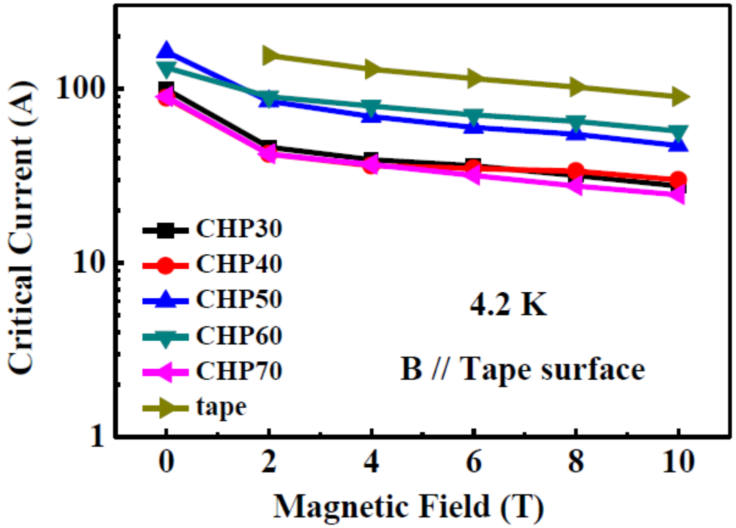
25

Development of superconducting joints between iron-based superconductor tapes





The diffusion bonding of IBS joint was achieved by the hot pressing



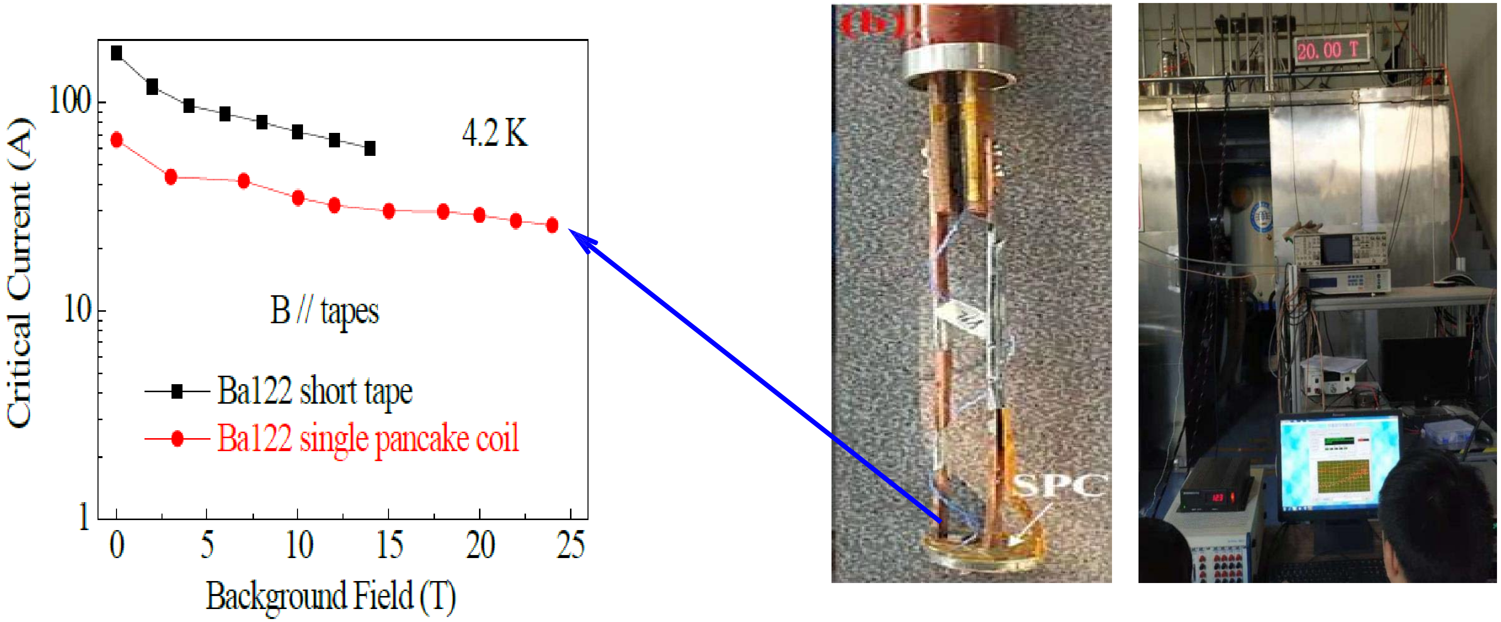
- **A superconducting joint is very important for persistent current operation.**
- **Transport I_c of 57 A for the joint was obtained, which is 63.3% of the tapes (10T @4.2K).**
- **Critical current ratio (CCR=Ic^{joint}/Ic^{tape}) of 63.3%.**

Zhu et al., ***SuST*** 2018 (31) 06LT02

Transport I_c-B curve for inserted coils

--Measured at HMFL in Hefei

25T-HM, RT bore
Φ38 mm



The I_c of the Ba122 coil showed weakly dependent on the magnetic field, like the short tape. (I_c=26 A in a field of 24 T)

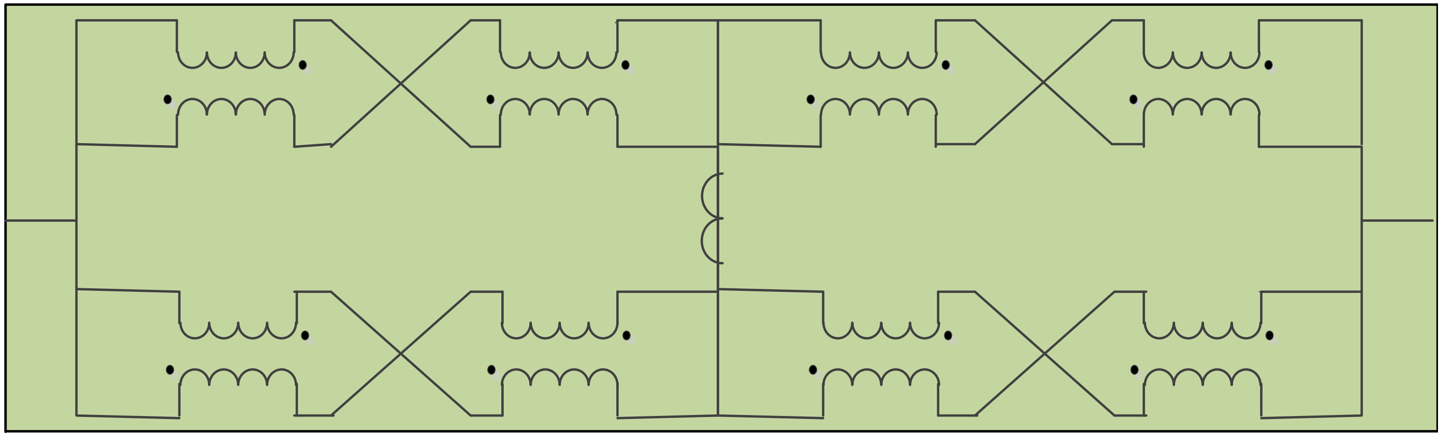
Content

- Materials for Large-Scale Application;
- Power Applications;
- Superconducting Magnet;
- Maglev;

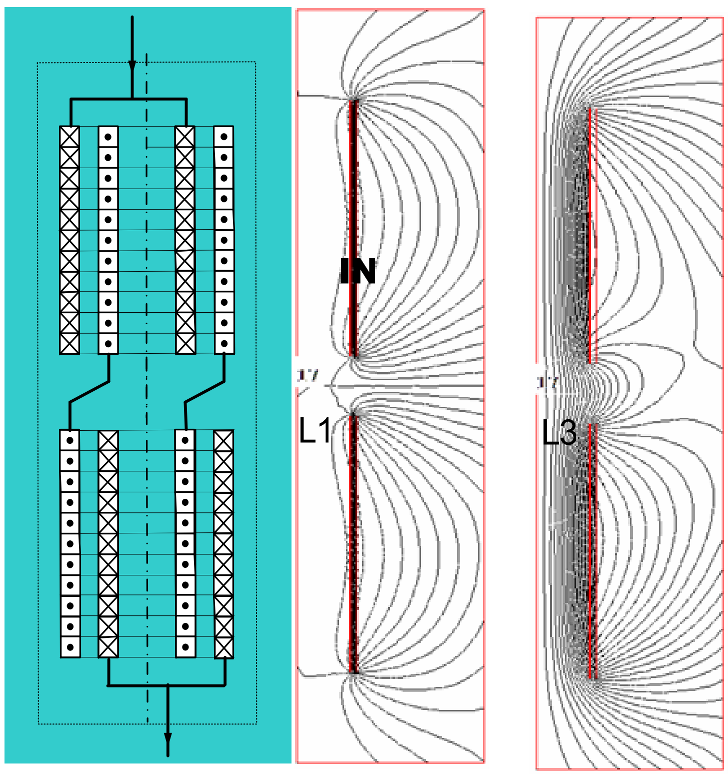
IEE: Development of a 40kV/2kA DC FCL

Circuit Topology of the DC FCL

The FCL could generate an inductance and smaller resistance at the beginning of the fault, but show smaller inductance and large resistance finally to limit the fault current.



Configuration design of a DC FCL module



connection of the coils | double-branches scheme | single-branch scheme

Magnetic field distribution of the DC FCL module

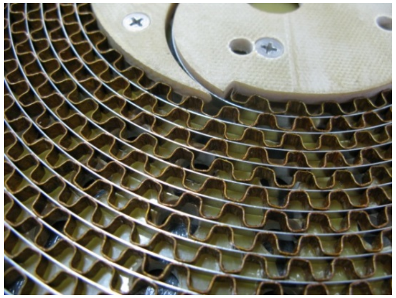
L4

L2

Coil Diameter/mm	176/216
Turns #	52
Height/mm	727
Inter-turn Insulation/mm	1.5
Operation Temperature/K	65-77

The Design of a module

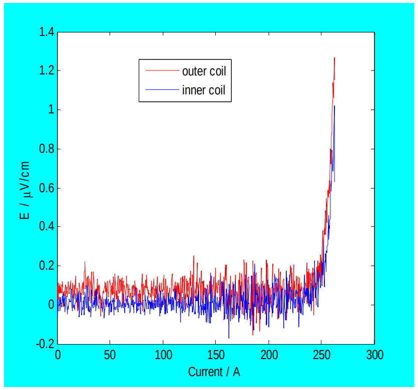
HTS pancakes for a DC FCL module



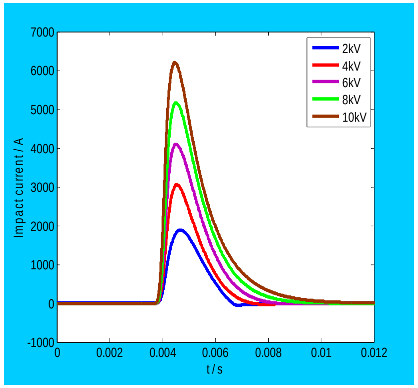
Test of A DC FCL module -10kV/400A

- **The 10kV/400A-2Ω FC-SFCL module is designed and manufactured. The critical current is about 500A, and the short-circuit current could be limited from 12kA to 6kA ;**
- **When the dc impact voltage is 10kV, the maximum resistance is about 0.8Ω when recovery time is set at 300ms and impact current is 2.2kA~5.5 times of the rated current.**

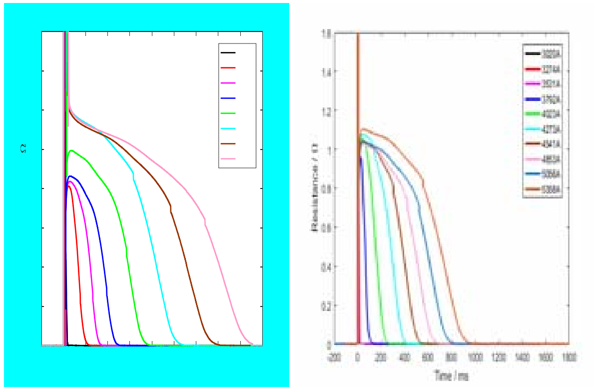
DC FCL module



The critical current test results



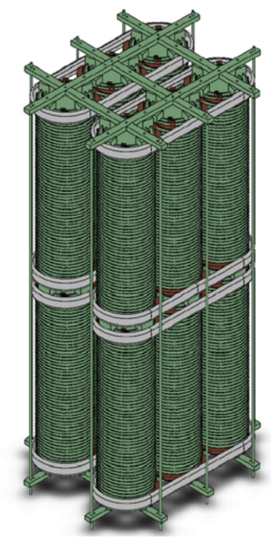
The impact current test results

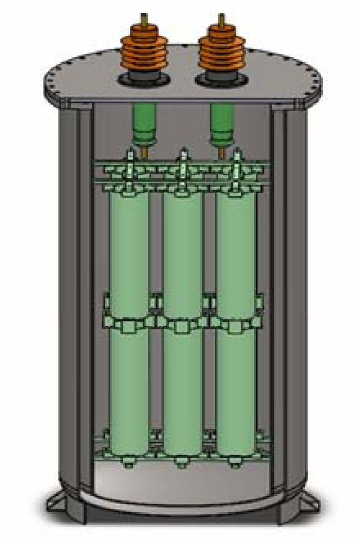


The resistance test results (10ms, 5ms)

Design of a 40kV/2kA DC Fault Current Limiter

- The Current Limiter consists of 6X4 modules, the deign is listed at the table.



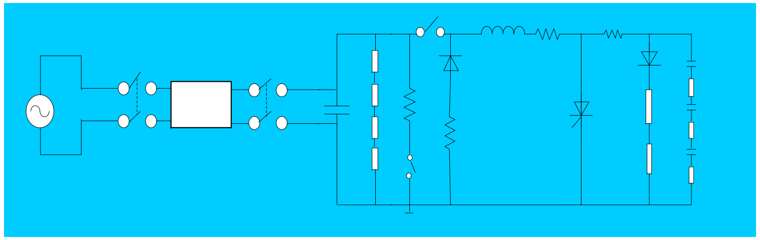


40kV/2kA DC Fault Current Limiter

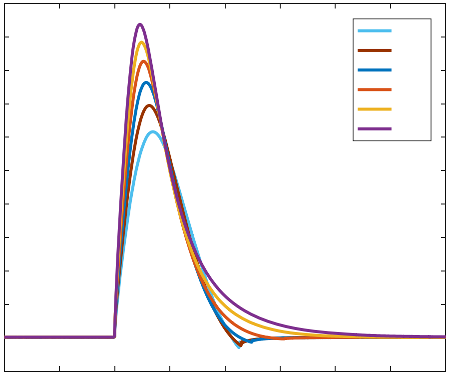
Number of Modules	6X4
Height/mm	1600
Outer Diameter/mm	800
Length of YBCO Tape/m	800
Operation Temp./K	65-77
Pressure at the Dewar	1 atm
Rated Voltage/kV	40
Critical Current/A	1200@77K；2500@65K
Rated Current/A	2000@65K

Fabrication of the Fault Current Limiter

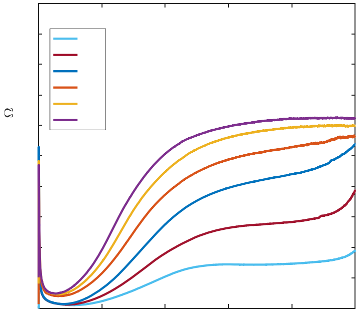
Test of the Fault Current Limiter



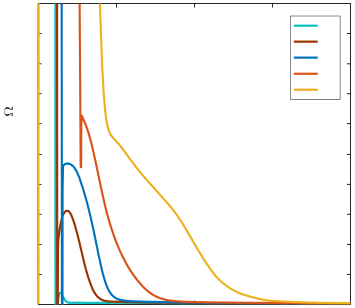
Circuit of the test facility



Impact Current



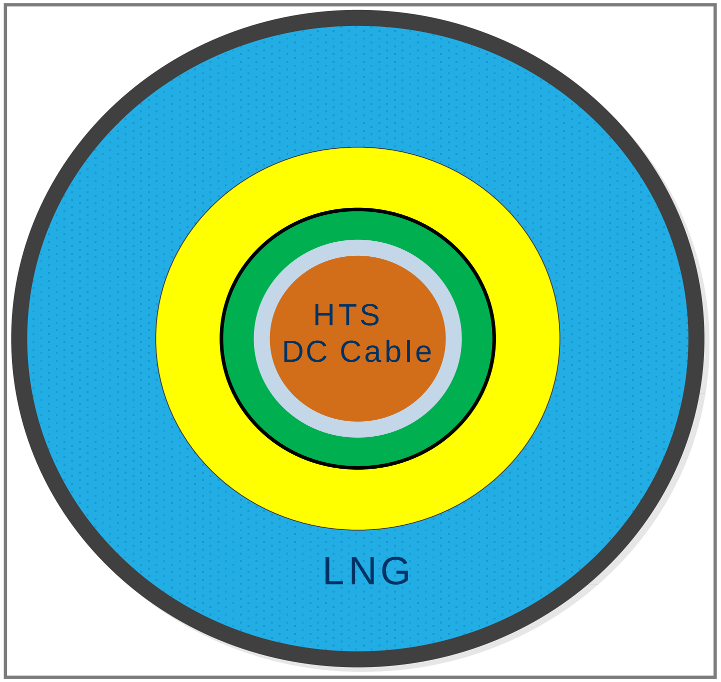
R-T during current impact



Quench Recovery

HTS energy pipeline @ LNG temperature

A Concept of HTS Energy Pipeline



V~200kVdc
I~25,000 A
P~10 GW
T~90-100K

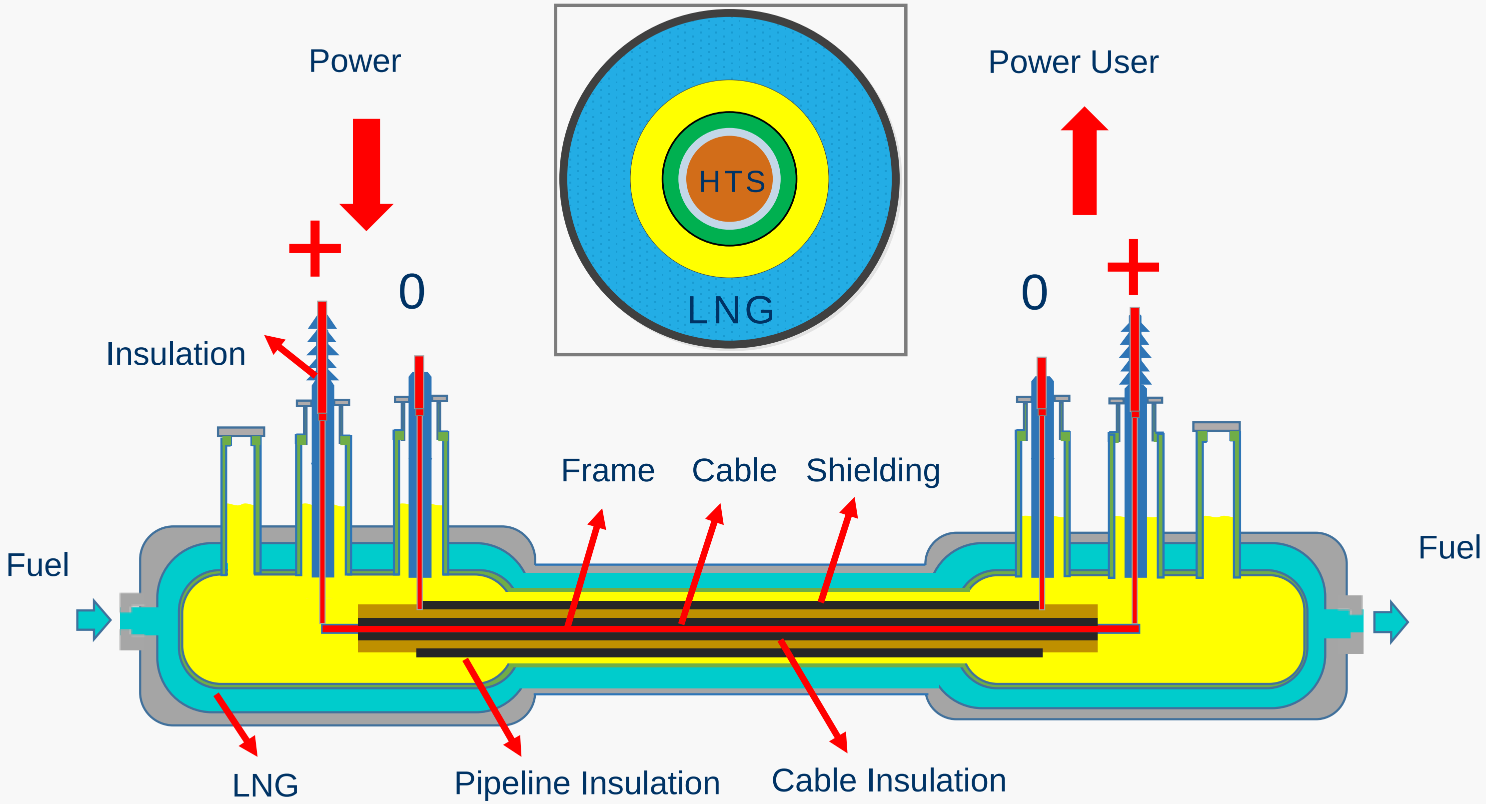
The energy (fuel and Electricity) transmission routes from the western to the eastern area in China

Electricity transmission in China

Natural Gas transportation in China

If the LNG and electricity can transferred by one superconducting energy pipeline, it would be a potential solution for China’s future energy transmission system.

IEE-CAS: Superconducting Energy Pipeline



Design of a 10m/10kV Superconducting Energy Pipeline

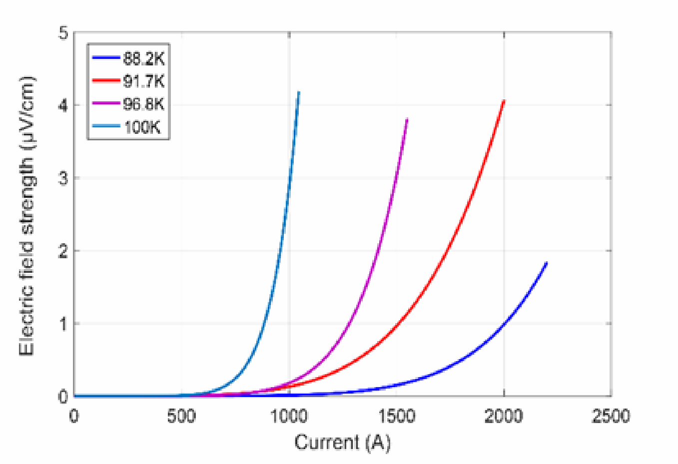
Superconducting cable for the Energy Pipeline

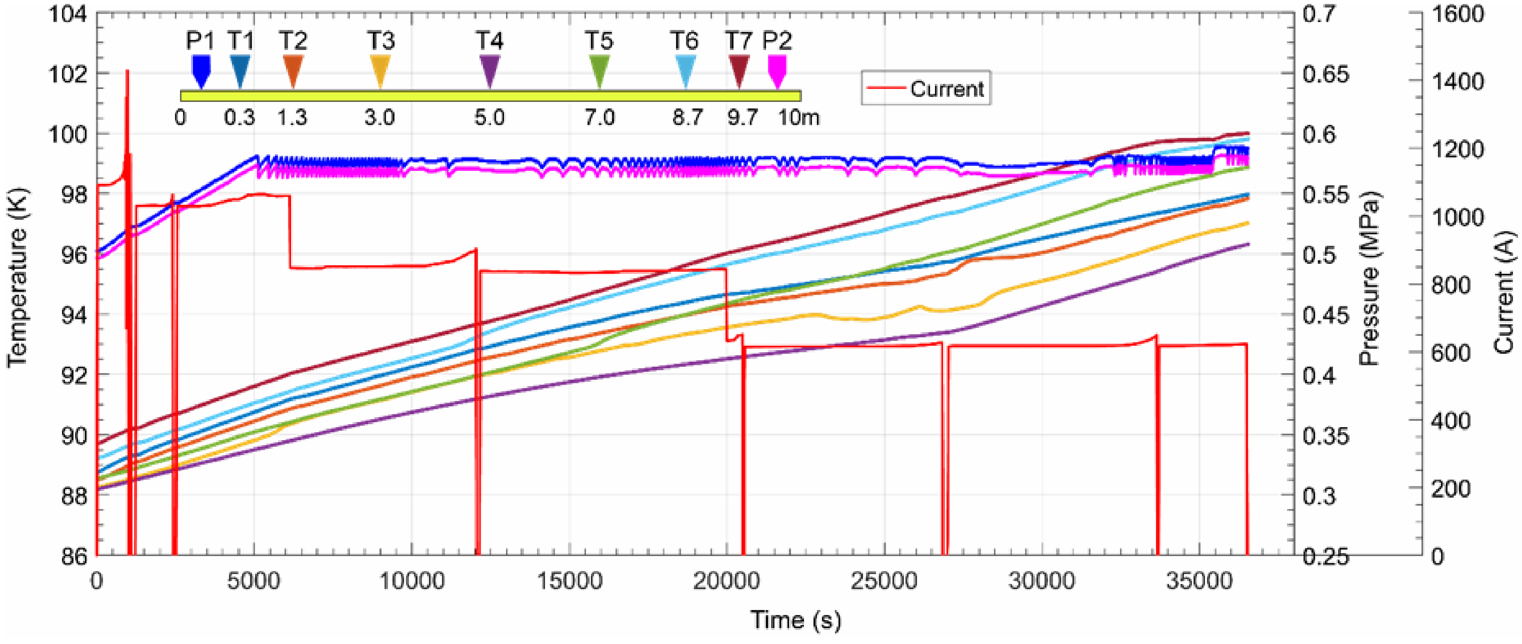
Design of HTS Cable Conductor

Parameter	Number of tapes
Outer diameter of former	25.7
Inner/Outer of conductor	25.8/28.1
Inner/Outer of insulation	30.0/36.0
Outer diameter of HTS cable	40.0
Critical current (A)	800A@100K

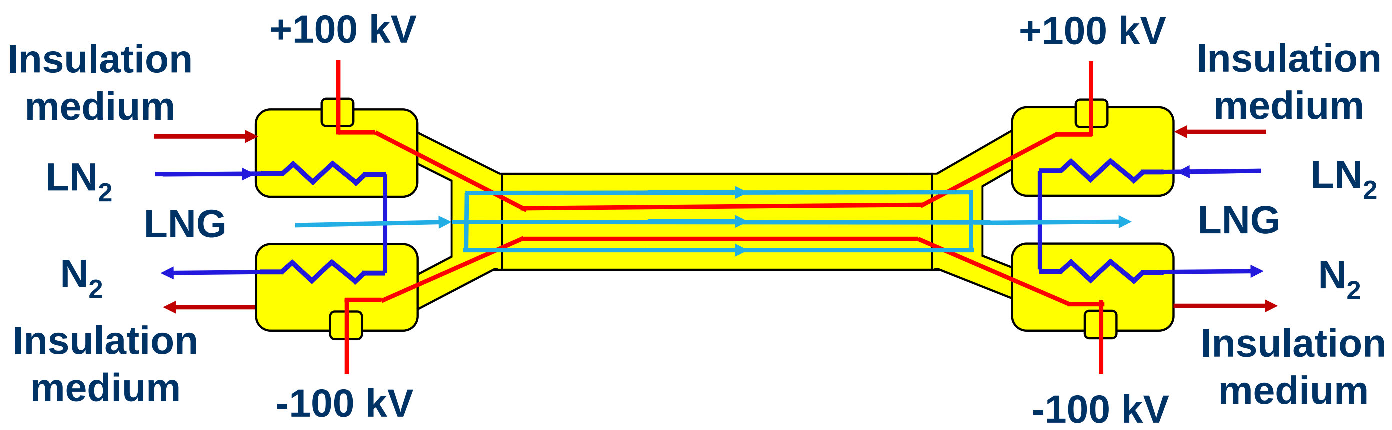
Overview of the Prototype Energy Pipeline Under Test

Test of the Energy Pipeline @15 litre/min of LNG





30m, ± 100kV/1kA Energy Pipeline is in fabrication



Shanghai Cable Institute: HTS Power cable

2005
Fabrication Equipments for HTS power Cable

2010
30m、CD HTS Power Cable prototype, after fabrication

2012
10m cable prototype tested before grid connection

2013
3phase, 50m, 35kV-2000A , in operation

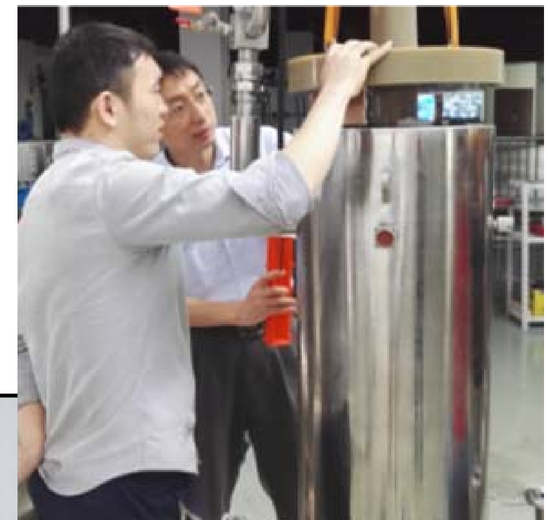
2016~2020
New project for 1.2 km cale

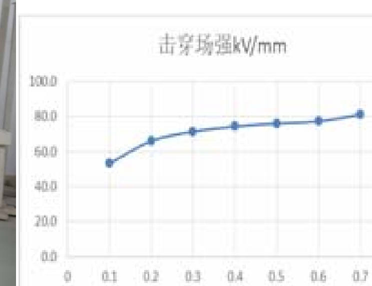
1.2 km HTS Cable Project in Shanghai Downtown Grid

1.2 km cable between two 220kV grid substations with 2200A at Xuhui district in Shanghai under construction

- **One SC cable may supply with 2000A for 30-50 thousands of families**

Insulation Design and Test

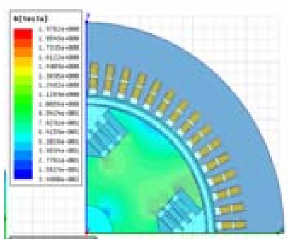




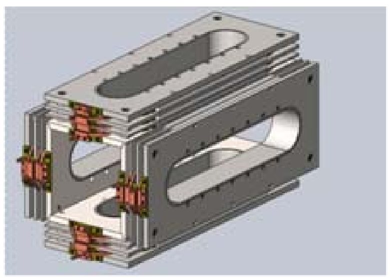
Fabrication of the terminator and Cryogenic tube for the cable

IEE/Shanghai Electric: 500 kW/690 V HTS Generator

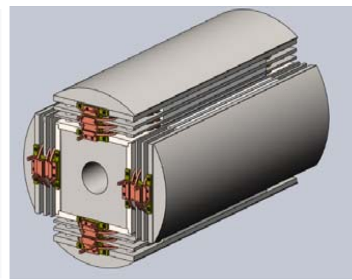
Parameters and structure of the HTS Generator



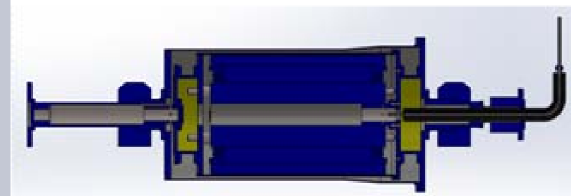
Distribution of the field



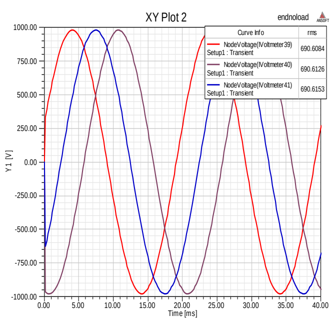
YBCO field winding



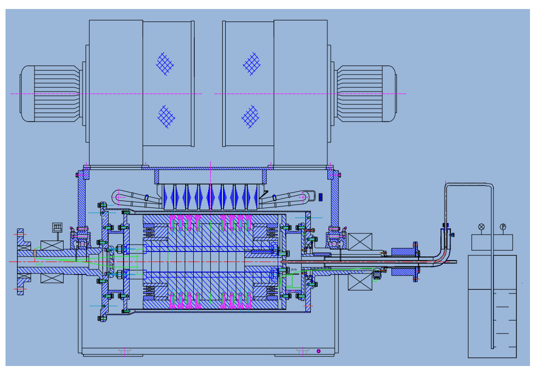
Rotor of the HTS generator

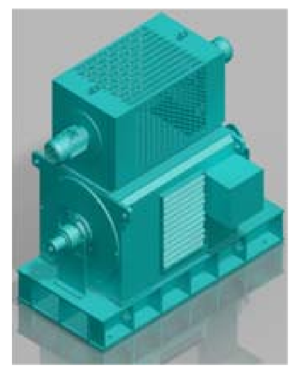


Cryogenic system of the HTS generator



The curve of rated voltage





Structure of the HTS generator

Parameters of the HTS generator

Items	Parameters
Rated Output Power	500 kW
Poles	4
Rated Voltage	690 V
Rated Field Current	30 A
Efficiency (Rated Load)	96.33%
Operating Temperature	77 K
Vibration (Rated Load)	1.6 mm/s
Noise (Rated Load)	99 dB

45

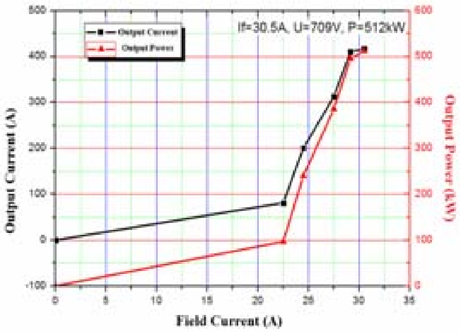
IEE/Shanghai Electric: 500 kW/690 V HTS Generator

YBCO racetrack coil

Superconducting rotor system

Stator

500 kW HTS generator system



Rated load test

上海电气
SHANGHAI ELECTRIC

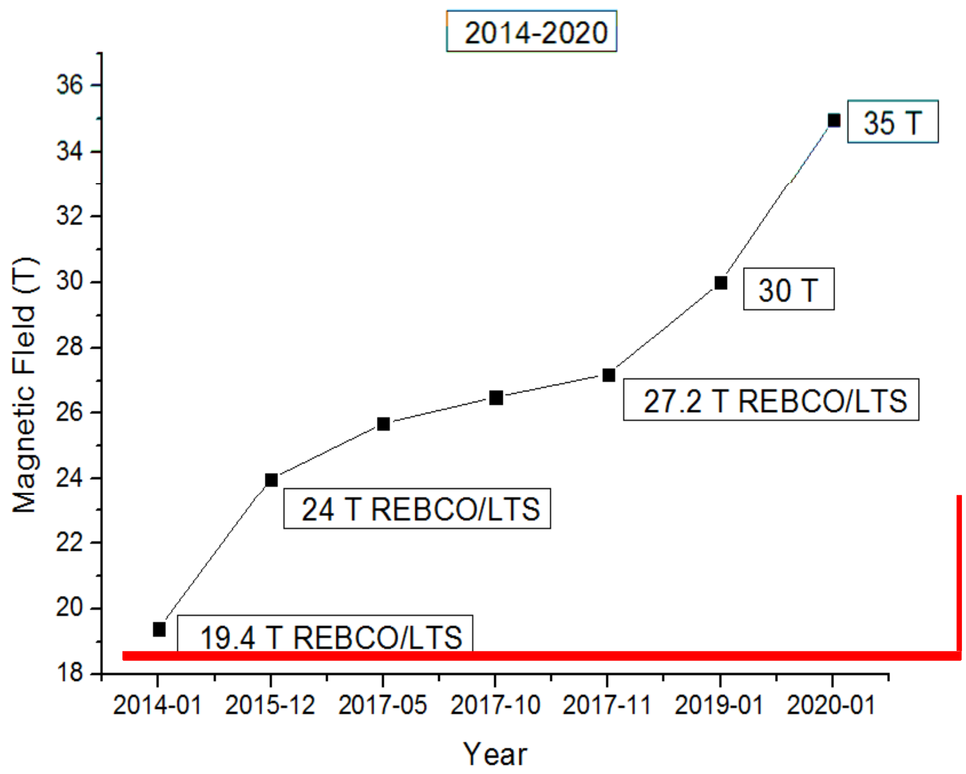
Content

- HTS Materials for Large-Scale Application;
- Power Applications;
- Superconducting Magnet;
- Maglev;

IEE: Design and fabrication 9.4 T magnet for MRI

Length of magnet	3500 mm
Height of magnet	1842 mm
Center field	9.4 T
Warm bore	800 mm
Total turn	118764
Total inductance	5286 H
Stored energy	138 MJ
Volume of LHe	~ 1000 l
homogeneity	<±0.1ppm(DSV 300mm)
Stability of field	<0.02ppm/h

The achievements of high field magnet at IEE

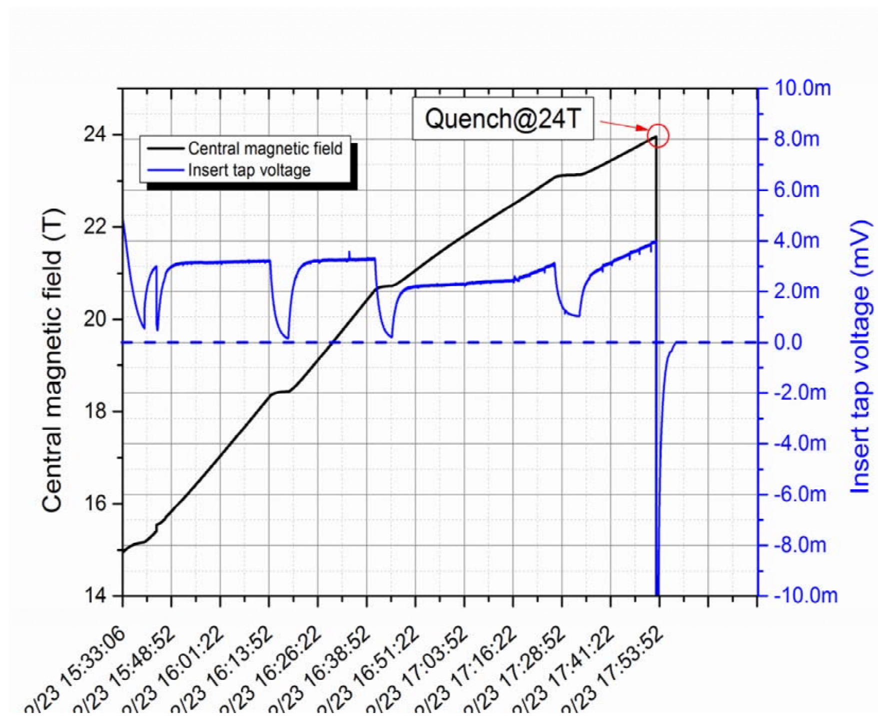


Future Plan

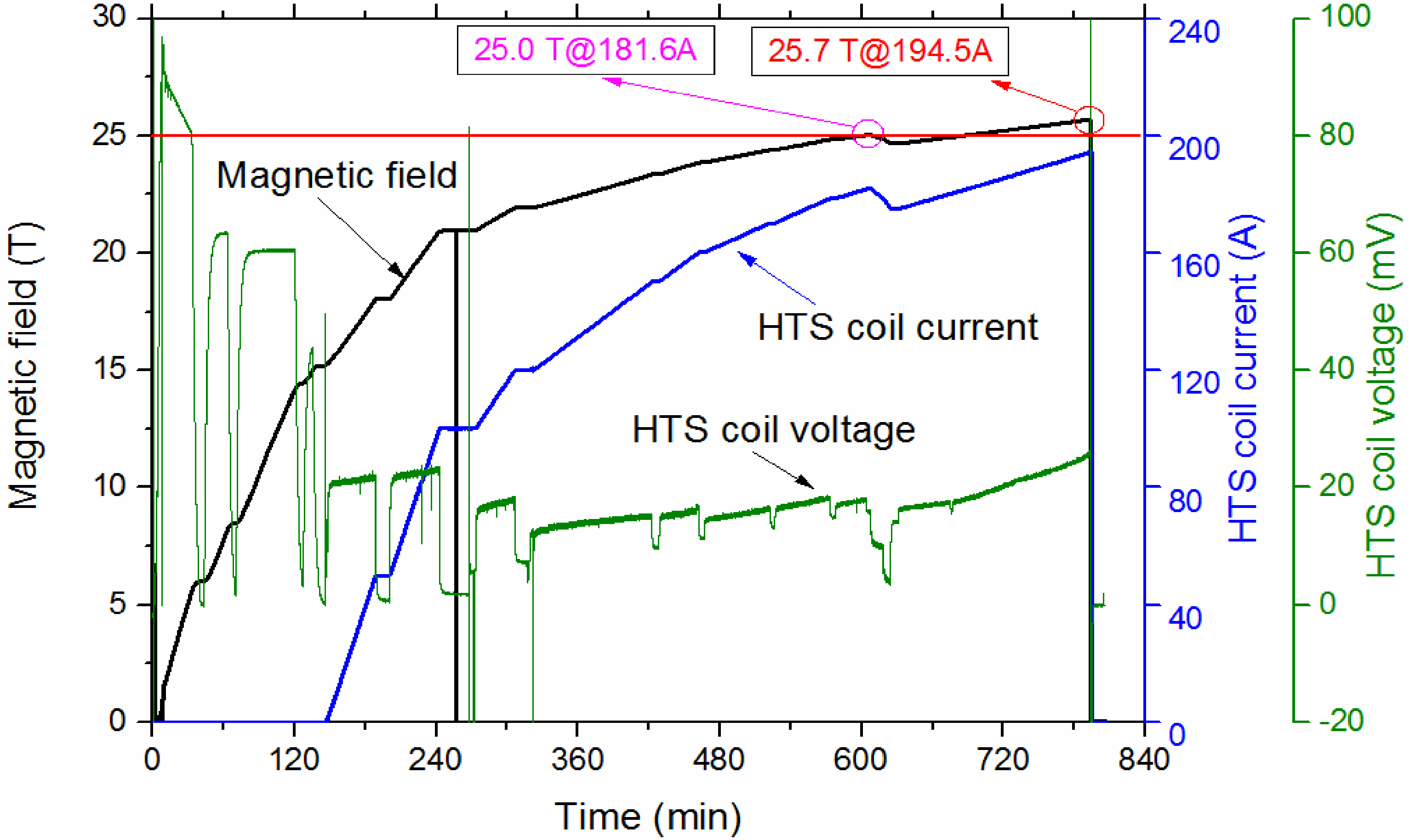
Recent Achievements

IEE-CAS: 24.3-32.5 T all-superconducting magnet system

YBCO Insert in 9.3 T/ 35 mm
Background B =15 T/160mm



25.7T full superconducting magnet system



YBCO Insert in 10.7 T/40 mm;Background B =15 T/160mm

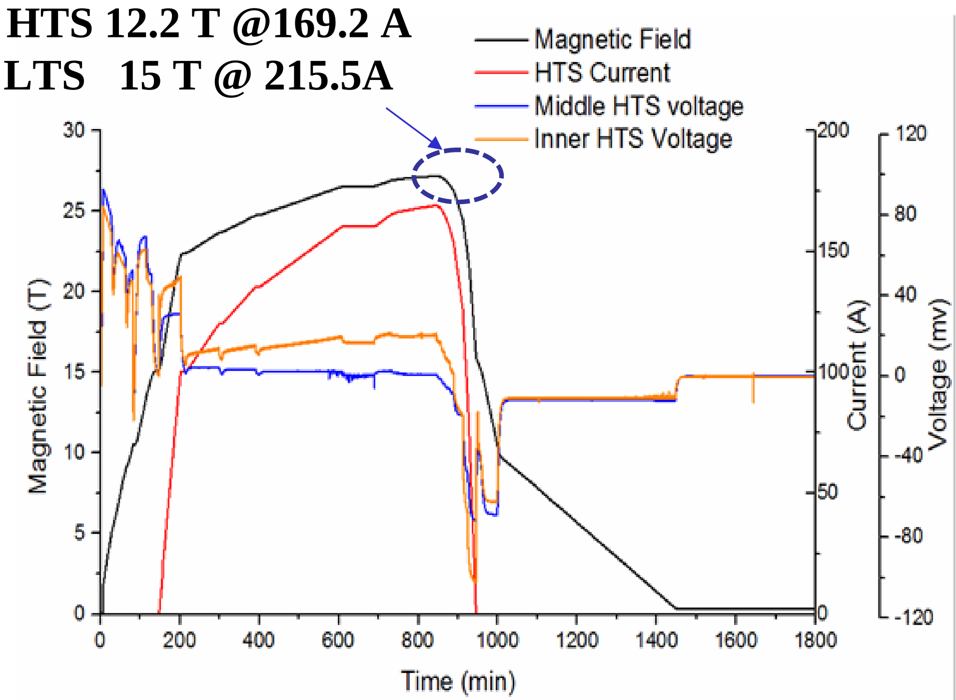
Design Parameters for 27.2 T

Parameters of the Inner and Middle HTS magnet

Parameter	Unit	Inner HTS coil	Middle HTS coil
Cold bore	mm	32	123
Number of DP		20	10
Insulation		Non-insulation	Non-insulation
Inner Diameter	mm	36	125
Outer Diameter	mm	109	149.2
Height	mm	200	100
Operating current	A	169.2	169.2
Operating temperature	K	4.2	4.2

- The Inner and Middle HTS insert coils are series connected and powered by a single Supply.

27.2T superconducting magnet system



- ➢ The LTS magnet supply 15 T at an operating current of 215.5 A
- ➢ The HTS magnet supply 12.2 T at an operating current of 169.2 A

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5
4
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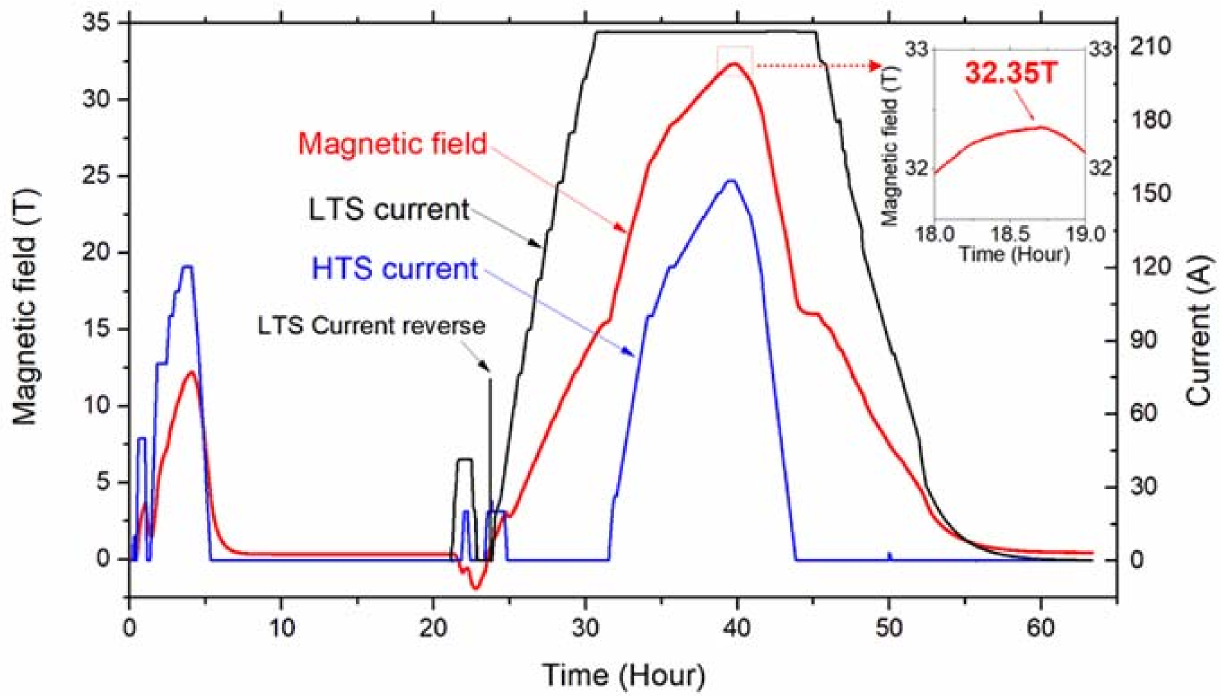
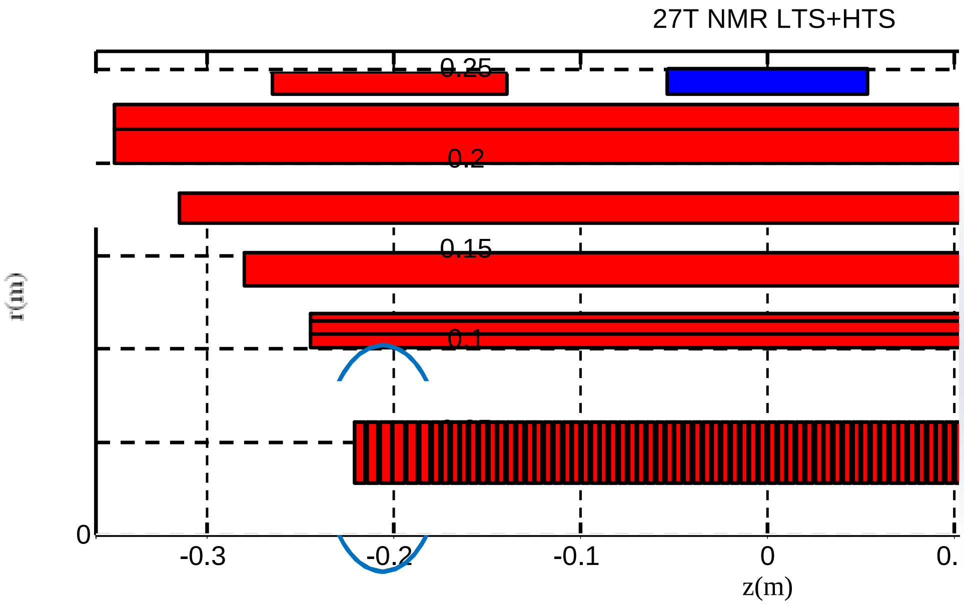
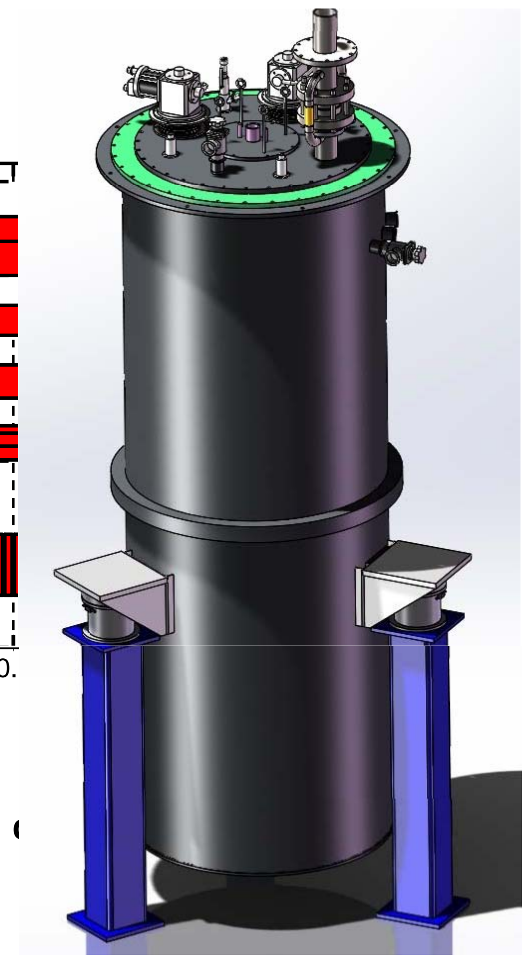
32.5T Reached at December, 2019



➢ **A new insert coil was used.**

A 25-27T Magnet for NMR is being in design

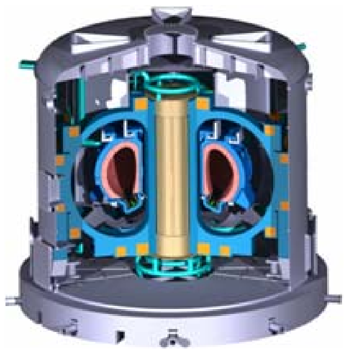




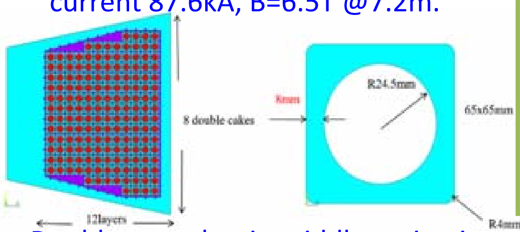
1.DP at ends with 6mm wide tape
2.Layer wound the HTS insert

IPP-CAS: China Fusion Engineering Test Reactor (CFETR)

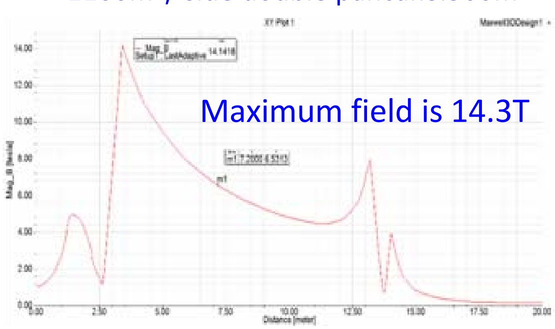
TF superconducting Coil for CFETR



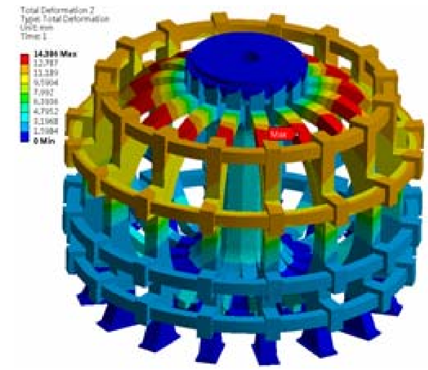
TF coil： Total turns of 168， operation current 87.6kA, B=6.5T @7.2m.



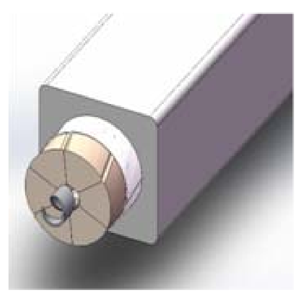
Double pancakes in middle region is 1100m，side double pancake:500m

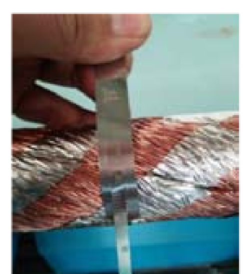


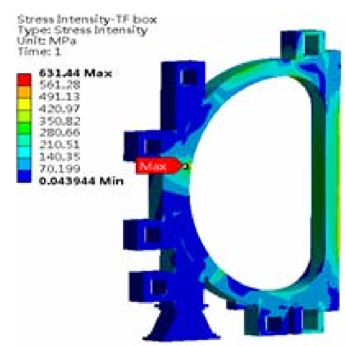
- I_p=14 MA,
- B_{to} = 6.5T,
- R_0 = 7.2 m ,a = 2.2 m
- P_{fusion} : 200MW-1000MW
- TBR > 1
- Duty time ≧ 0.5



- Generates steady-state burning plasmas (duty time ~ 50%)
- Tests the self-sustainable burning (Q ≧ 25~30, H α ~ 83-86%)
- Realizes Tritium self-breadingR&D for structural and functional materials which have high neutron flux resistive

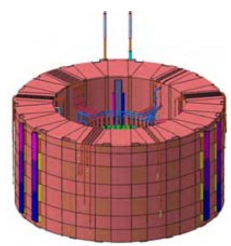


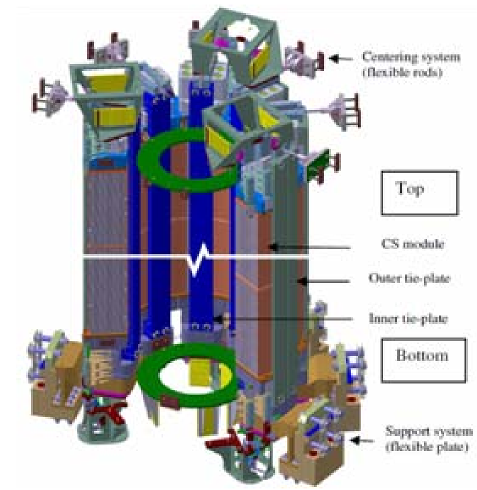




CS Coil and PF coils for CFETR

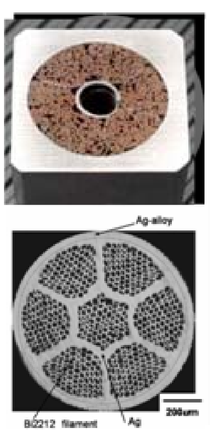
COILS	R(m)	Z(m)	△R(m)	△Z(m)	TURNS
CS1U	1.70	1.025	1.0	2.05	738
CS2U	1.70	3.075	1.0	2.05	738
CS3U	1.70	5.125	1.0	2.05	738
CS4U	1.70	7.175	1.0	2.05	738
CS4L	1.70	-7.175	1.0	2.05	738
CS3L	1.70	-5.125	1.0	2.05	738
CS2L	1.70	-3.075	1.0	2.05	738
CS1L	1.70	-1.025	1.0	2.05	738

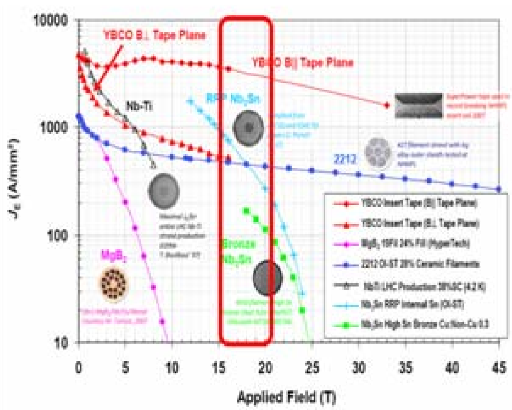




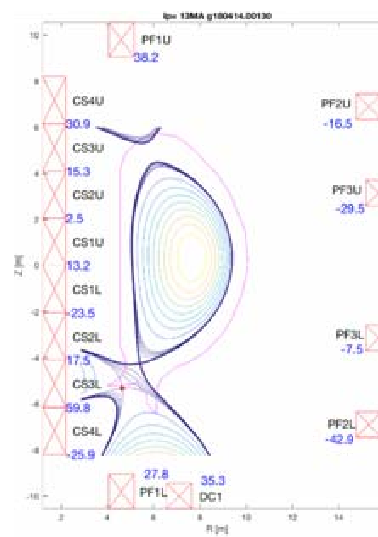
CS Conductor

- **material：** High Jc Nb_3Sn or Bi-2212
- **Conductor：** Cable-in-Conduit Conductor(CICC)





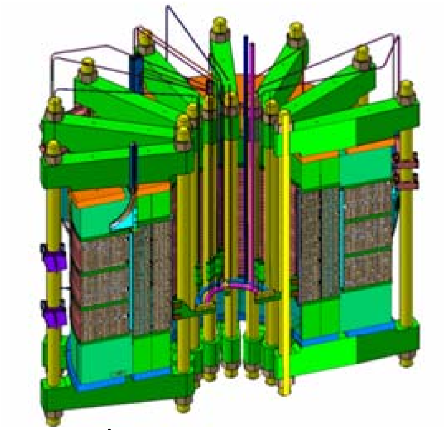
Coil	SN	SF+
	Maximum filed/T	
PF1U	5.2318	4.9051
PF2U	0.84155	0.85487
PF3U	3.8982	4.3090
PF1L	5.5761	4.4089
PF2L	1.4326	4.2372
PF3L	2.4204	0.6777
DC1	1.4498	4.4638



CFETR CS Model Coil

- **Winding of two Nb_3Sn were completed. The winding of NbTi coil is on-going**
- **The preparation of testing facility will be finished soon**

First Nb_3Sn coil

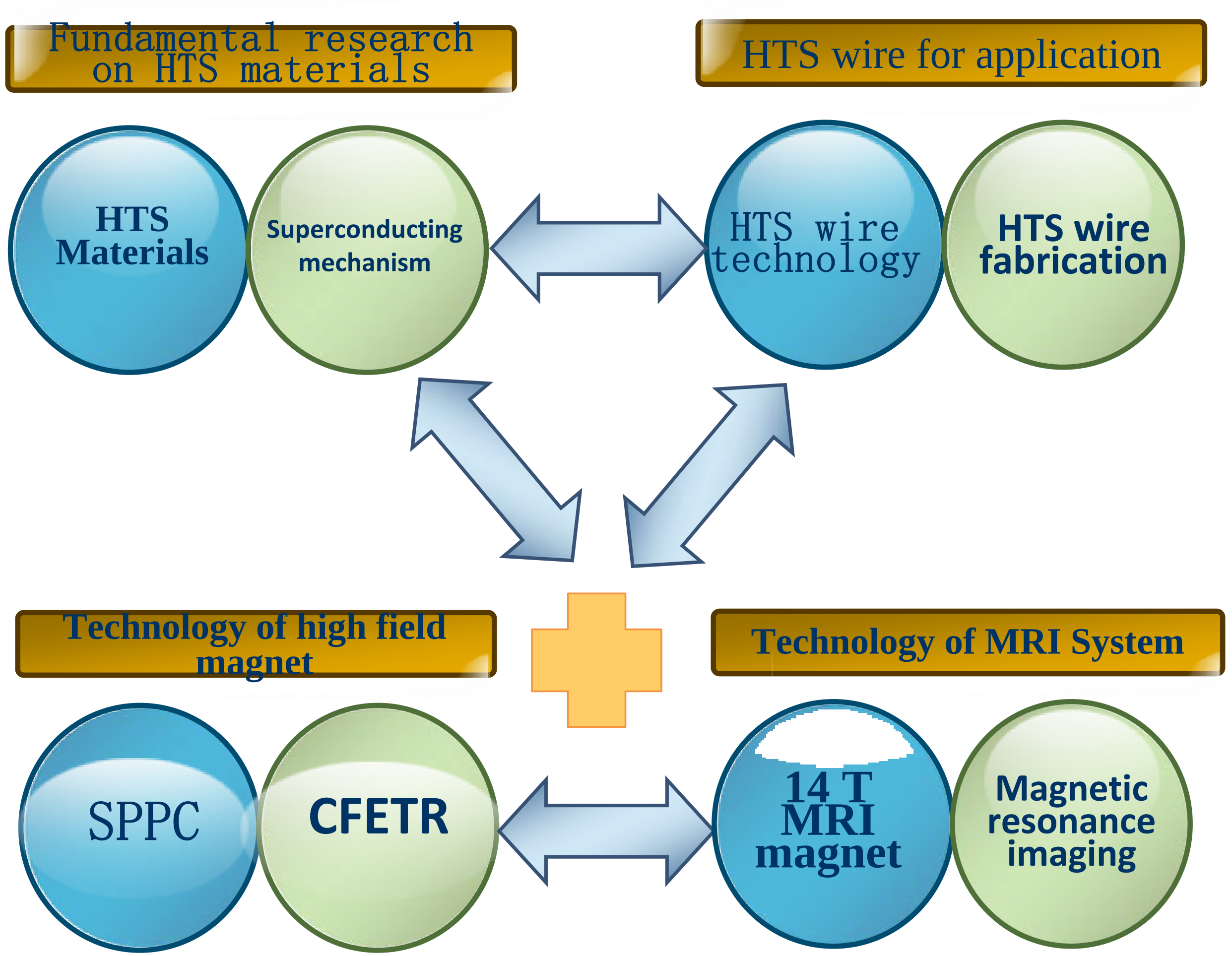


1/3 CFETR CS coil

NbTi coil winding

Testing facility

Program of the Chinese Academy of Sciences on HTS



Program of the Chinese Academy of Sciences on HTS

HTS Candidates
--IBS
--Bi2212
--ReBCO

↓

10 year Target

↓

-- Jc, increased by 10 times
-- Cost, reduced by 10 times

中国科学院战略性先导科技专项
立项建议书

Proposal for
Strategic Priority Research Program
of Chinese Academy of Sciences (CAS)

Science and Technology Frontier Research for High Field Applications of High Temperature Superconductors

5-Year Program first!
Officially approved in May 2018

专项申请总经费： 36000（万元）

Content

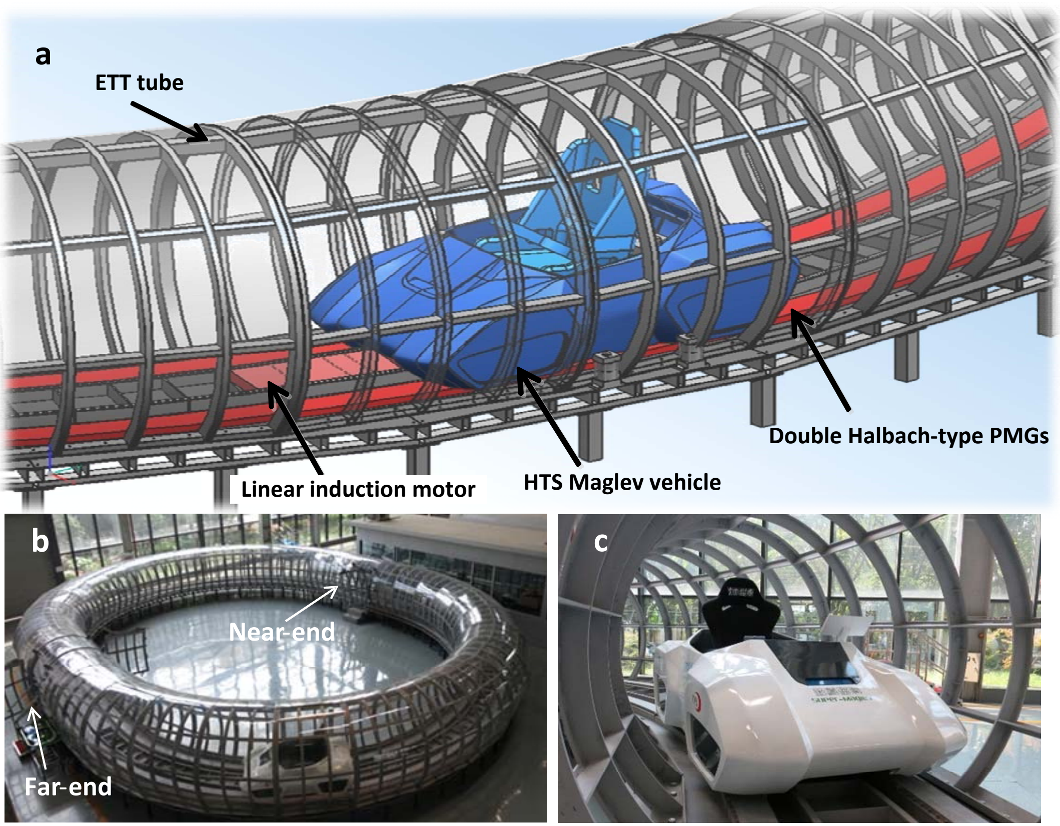
- HTS Materials for Large-Scale Application;
- Power Applications;
- Superconducting Magnet;
- Maglev;

HTS Maglev ring test line in Chengdu, China in 2013

- **Test line:** 45-m in total including two 3.6-m straight lines and two 6-m-radius curve-lines
- **Levitation height:** 10-20 mm
- **Load capability:** 300 kg for one passenger (maximum 1000 kg @ 10 mm)
- **Maximum speed:** 25 km/h

Zigang Deng, et al., *IEEE Trans. Appl. Supercond.* 26(6) 3602408, 2016.

First proof of "HTS Maglev" + "Evacuated Tube"



- HTS Maglev Carrier
- 2-m-diameter evacuated tube
- 1～0.1 atm pressure
- 50 km/h maximum

Zigang Deng, et al., *IEEE Trans. Appl. Supercond.*
doi:10.1109/TASC.2017.2716842

- **More than 2,000 visitors have experienced the HTS Maglev Vehicle;**

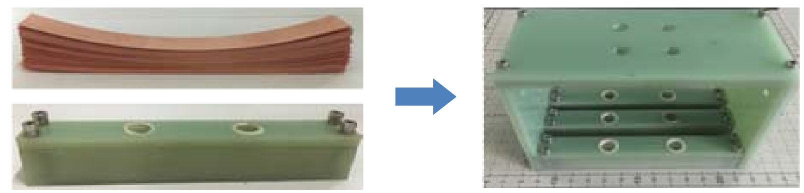
New HTS maglev with REBCO coated conductor stacks:

Hundred of REBCO sheets stacked to behave as a bulk

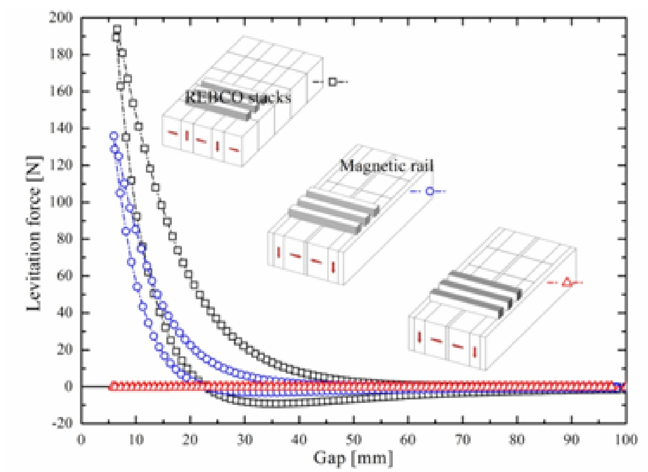
HTS tape versus HTS bulk:

higher Jc, better thermal stability, larger mechanical tolerance and anti-corrosion, more flexible in geometry, ……

But, the price is slightly higher



Three REBCO stacks were assembled to make a unit
that is comparable with the three-seed HTS bulk in geometry



The hysteretic loop of levitation force of
REBCO stacks over different magnetic rails

- The levitation force is comparable to that of the HTS bulk in similar dimensions
- The levitation performance is strongly dependent on the array of the REBCO stacks
- To further enhance the levitation capability of stack-type maglev, wider tape (e.g., 40 mm+) is needed to obtain a larger current loop

Stack-type maglev can use the waste REBCO tape
during the fabrication of HTS cable

Guangtong Ma*, et al., *Supercond. Sci. Techn.*, 31(8) 084001, 2018.
Guangtong Ma*, et al., *Supercond. Sci. Techn.*, 31(1) 015013, 2018.

Contributors to this presentation

- **Materials**

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- **Power Applications**

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- **Superconducting Magnet**

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- **Maglev**

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