Development of High Temperature Superconducting Magnet for Very High Field

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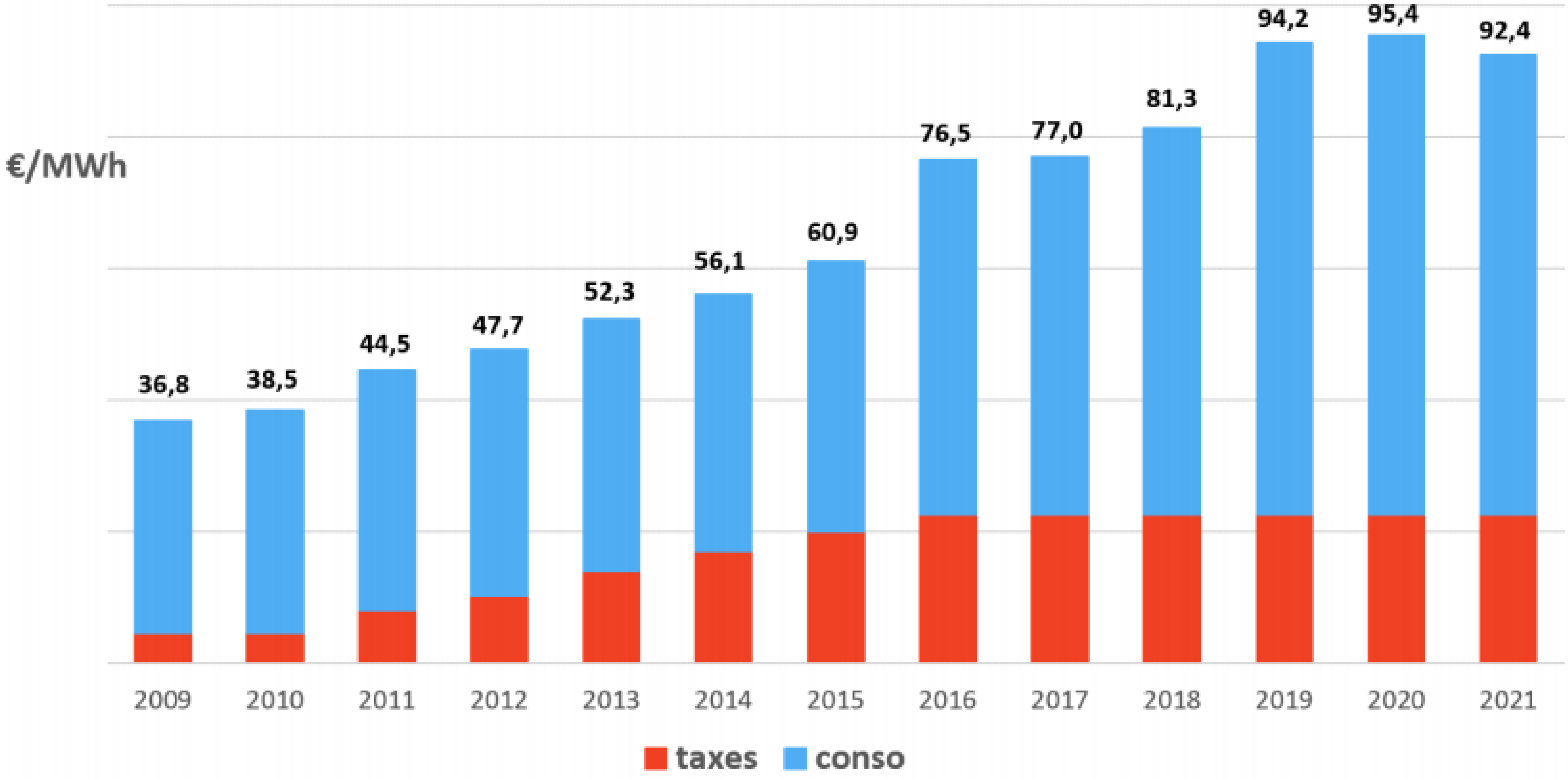
Rising energy price



Reference: 2021 annual report of LNCMI

Need to reduce energy consumption for production of high magnetic field

HTS projects in LNCMI

Finished project: NOUGAT for feasibility check of HTS insert for very high field magnet

To build and test a 10 T HTS insert in the 20 T background field of a resistive magnet

1. Ongoing HTS project - SuperEMFL

Design stage (phase1) for development of very high field all superconducting magnet (11 partners)

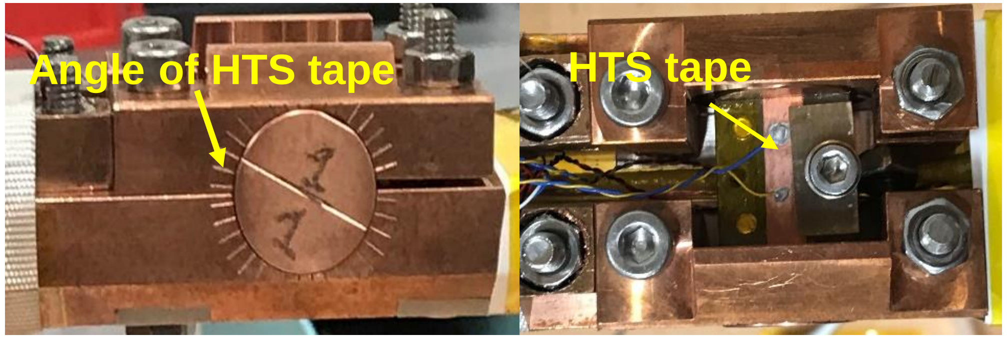
2. Ongoing HTS project - FASUM

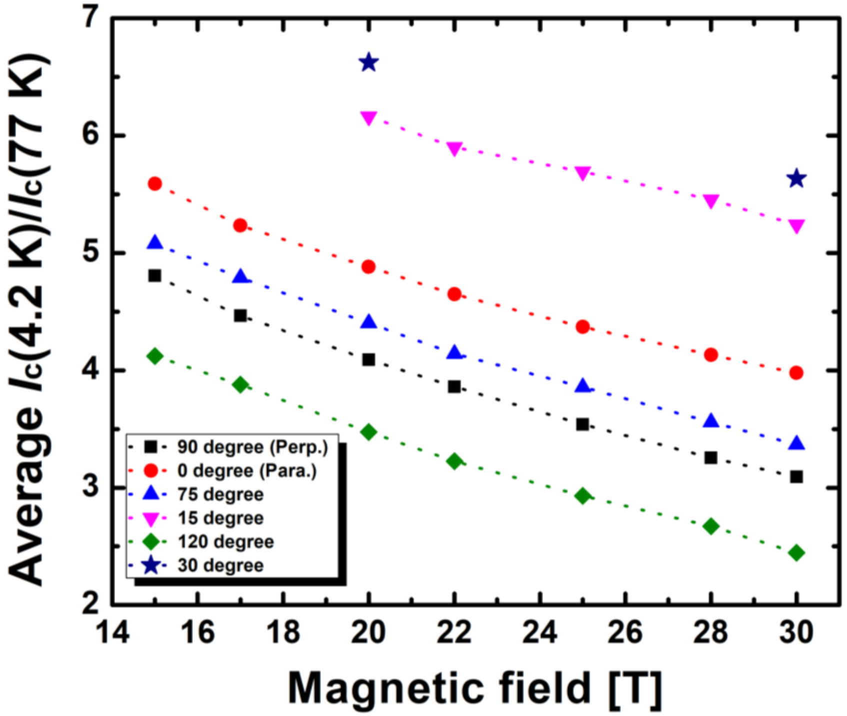
Construction and installation of all superconducting user magnet

(1) 40 T/25 mm all superconducting magnet or (2) 32 T/38 mm all superconducting magnet for end-users

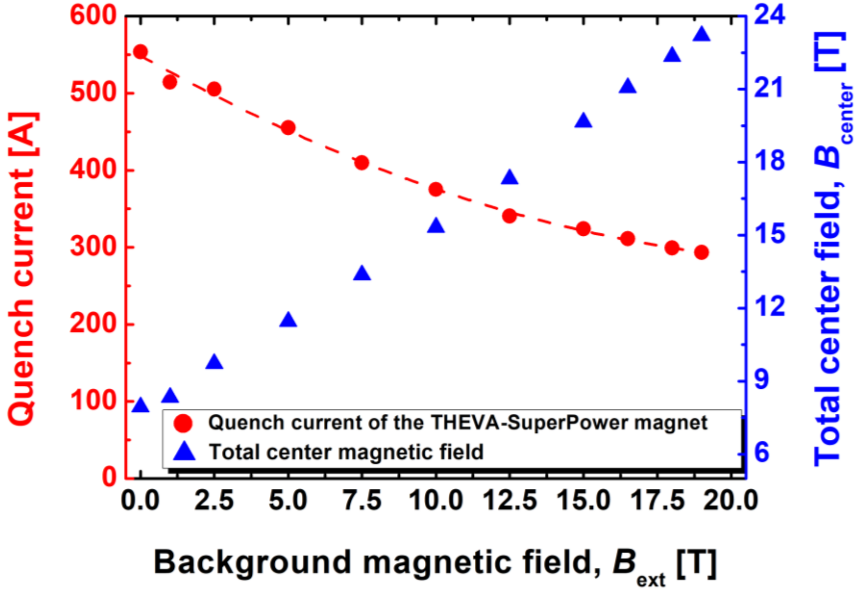
Characterization of HTS tape and magnet

1) Characterization of HTS tapes





2) Characterization of HTS magnets



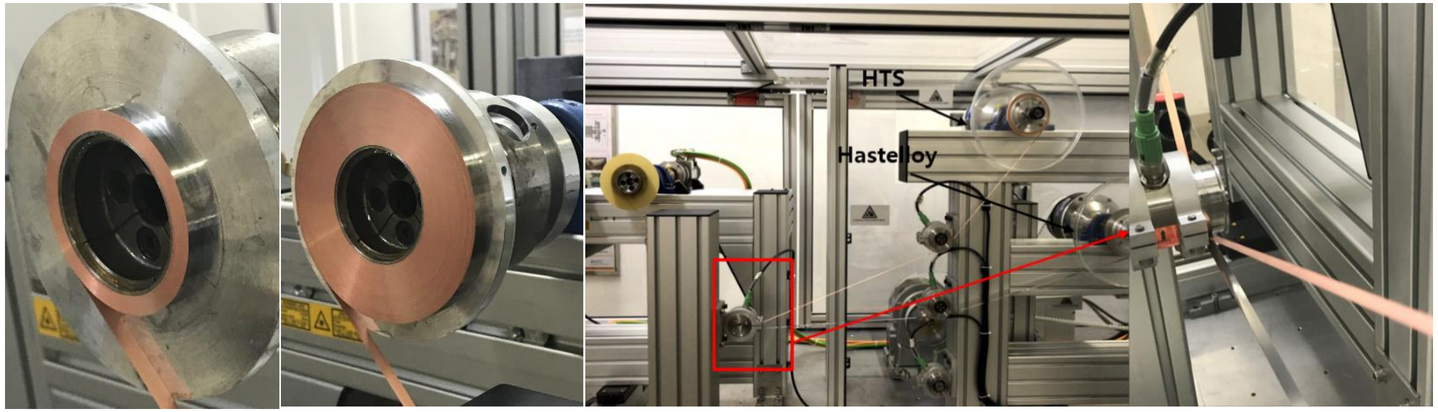
For SuperEMFL and FASUM projects, four HTS model magnets wound with various HTS tapes will be estimated under various external fields at 4.2 K.

Protection for HTS insert

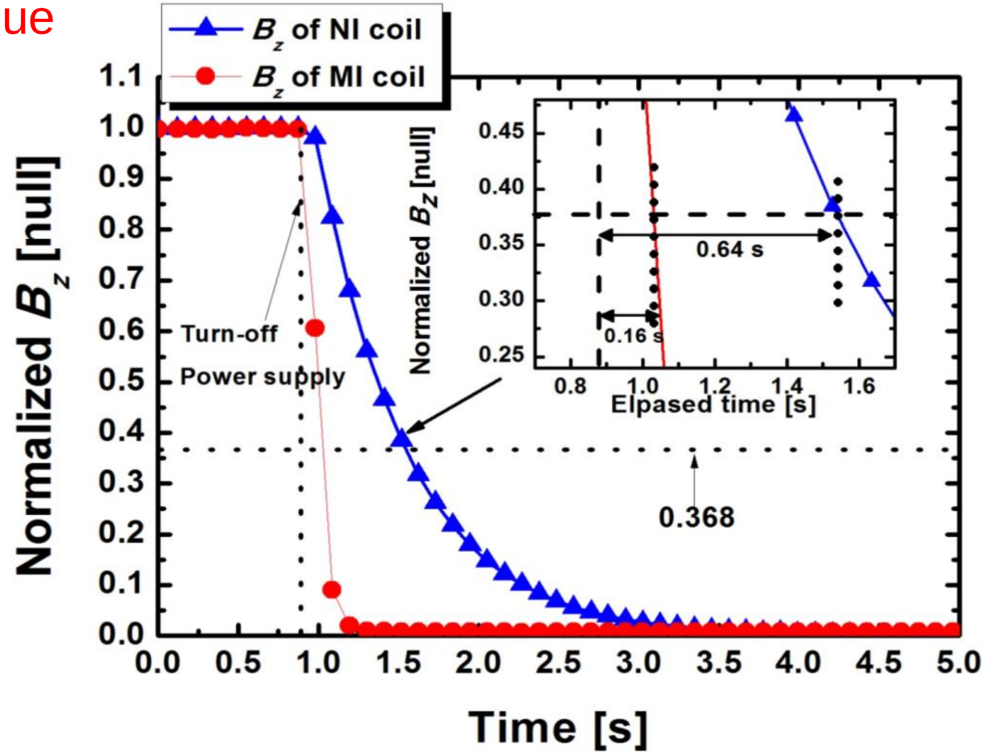
Metal-as-insulation (MI) winding technique

Cowinding with high electrical resistivity and strong mechanical strength tape

- To use self-protecting feature of no insulation (NI) winding technique
- To improve charging-discharging delay of NI magnet
- To reinforce mechanical strength of REBCO coils



MI winding technique



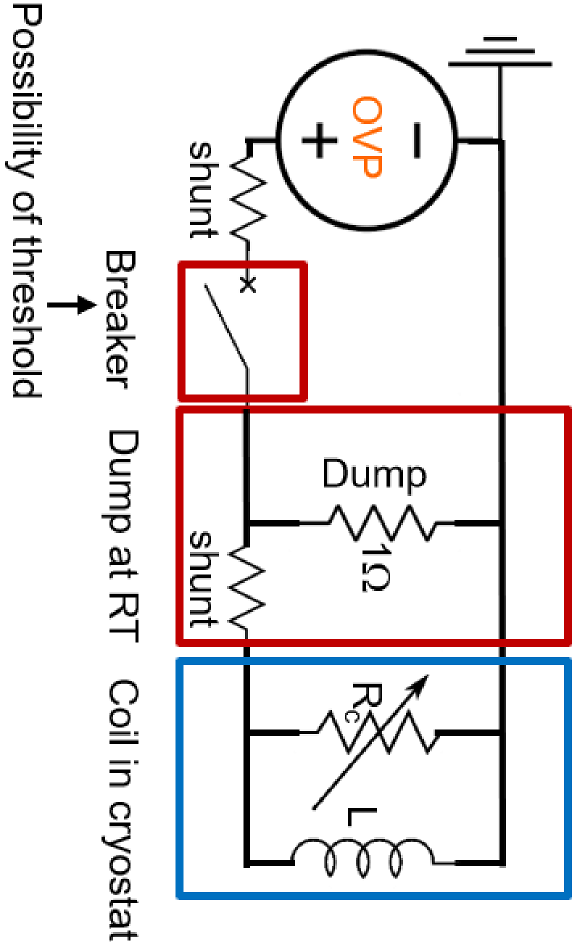
Sudden discharge test results of NI and MI REBCO coils

The metal-as-insulation (MI) HTS insert

A photograph of the MI HTS insert

Specifications of the MI HTS insert

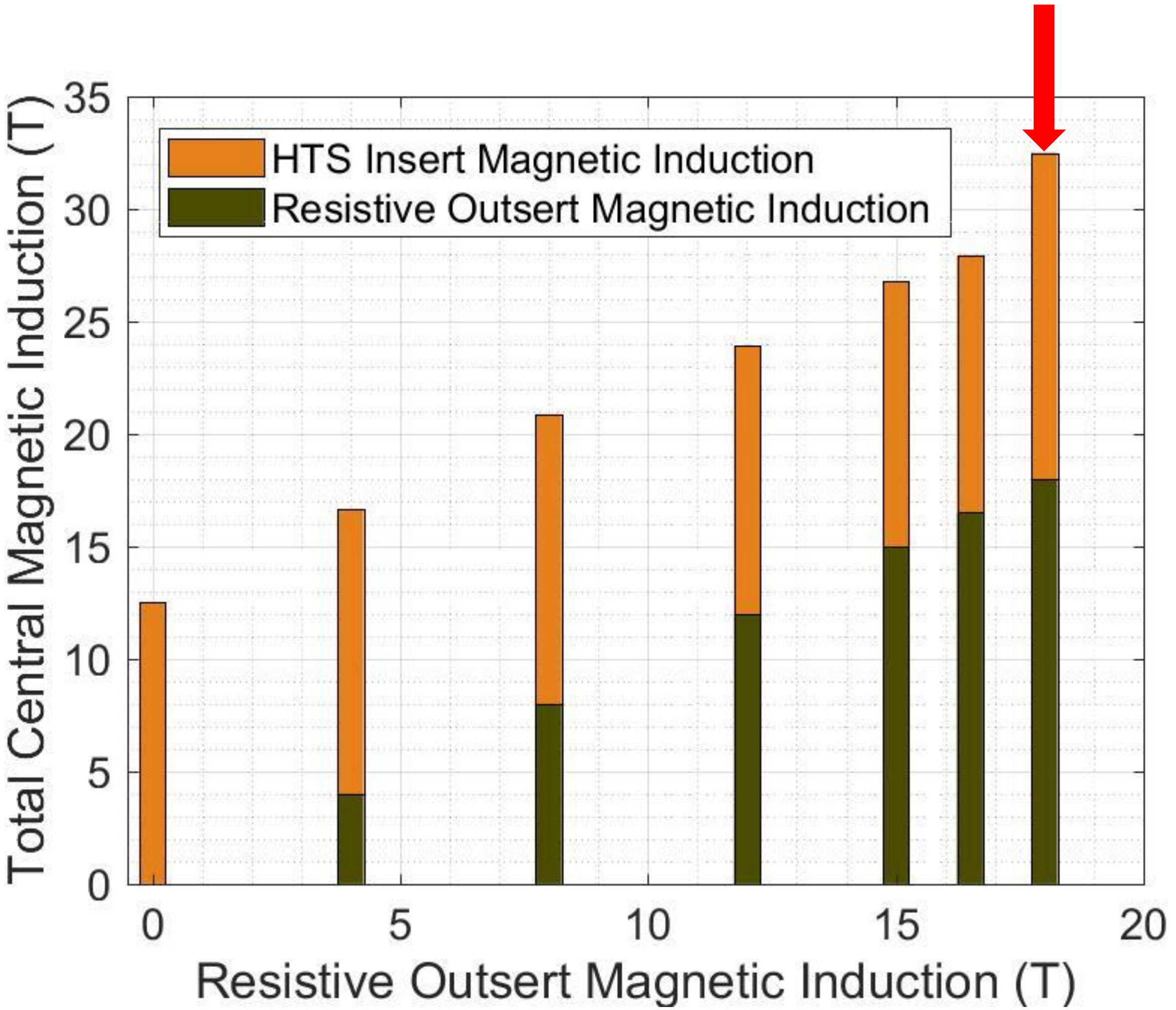
Parameters		Values
ID; OD	[mm]	50; 112
Height	[mm]	122.3
I_c values of DP coils at 77 K	[A]	54.5 ~ 67.3
Number of DP coils		9
Turn per pancake		290
Total conductor length	[Km]	~ 1.35
Thickness of SS for overband (OB)	[µm]	75
Number of SS OB turns		44
OD after SS OB	[mm]	118.8 ~ 119.0
Winding tension	[MPa]	92 ~100
Magnet inductance	[mH]	846.3
Magnet constant	[mT/A]	44.58
Time constant (τ) at 4.2 K	[s]	2.80
Characteristics resistance (R_c) at τ	[mΩ]	295.24
HTS turns btw OB for magnetic shielding		3



A electrical circuit diagram for protection of HTS insert

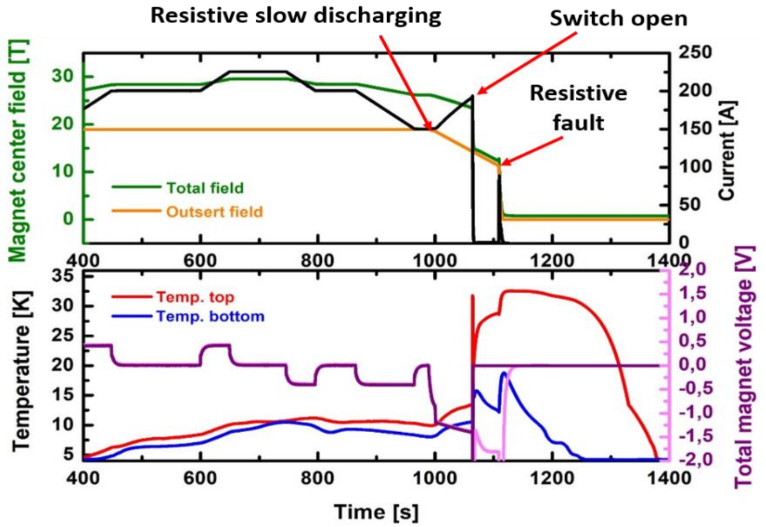
Test of the MI HTS insert

32.5 T
26 March 2019

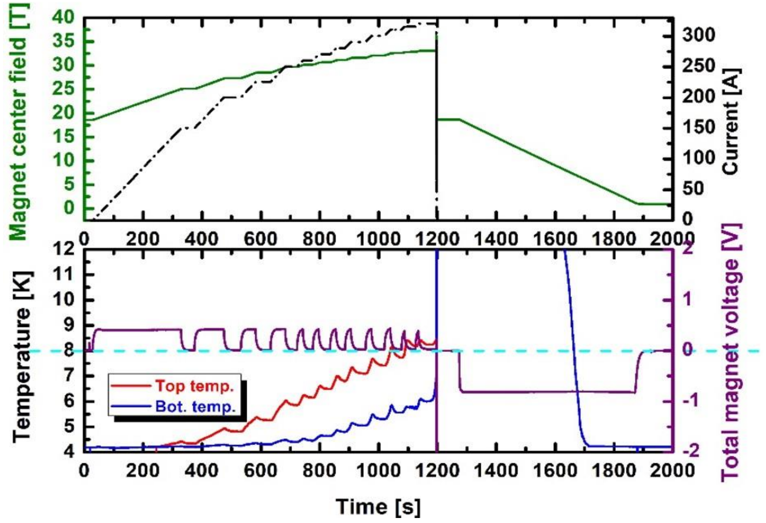


Two major events

1. 19 T resistive field discharge at B_{tot}=29 T

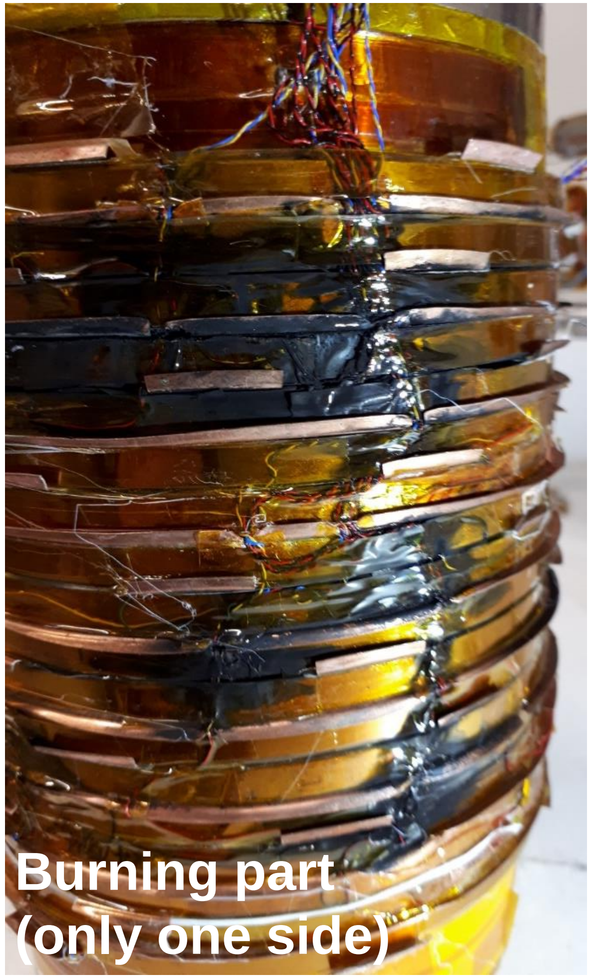


2. 32.5 T (14.5 T HTS) thermal quench

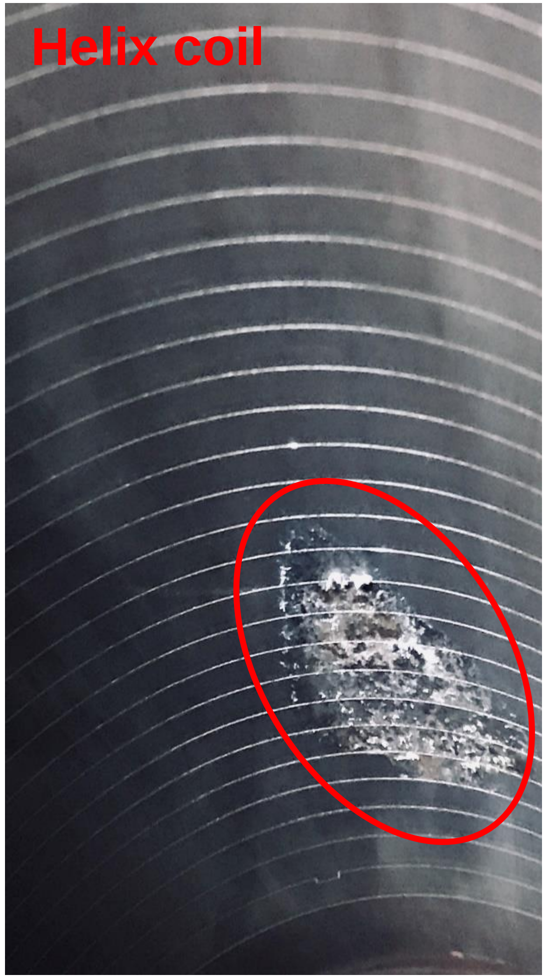


HTS insert and resistive outsert after 2 major events

MI HTS Insert

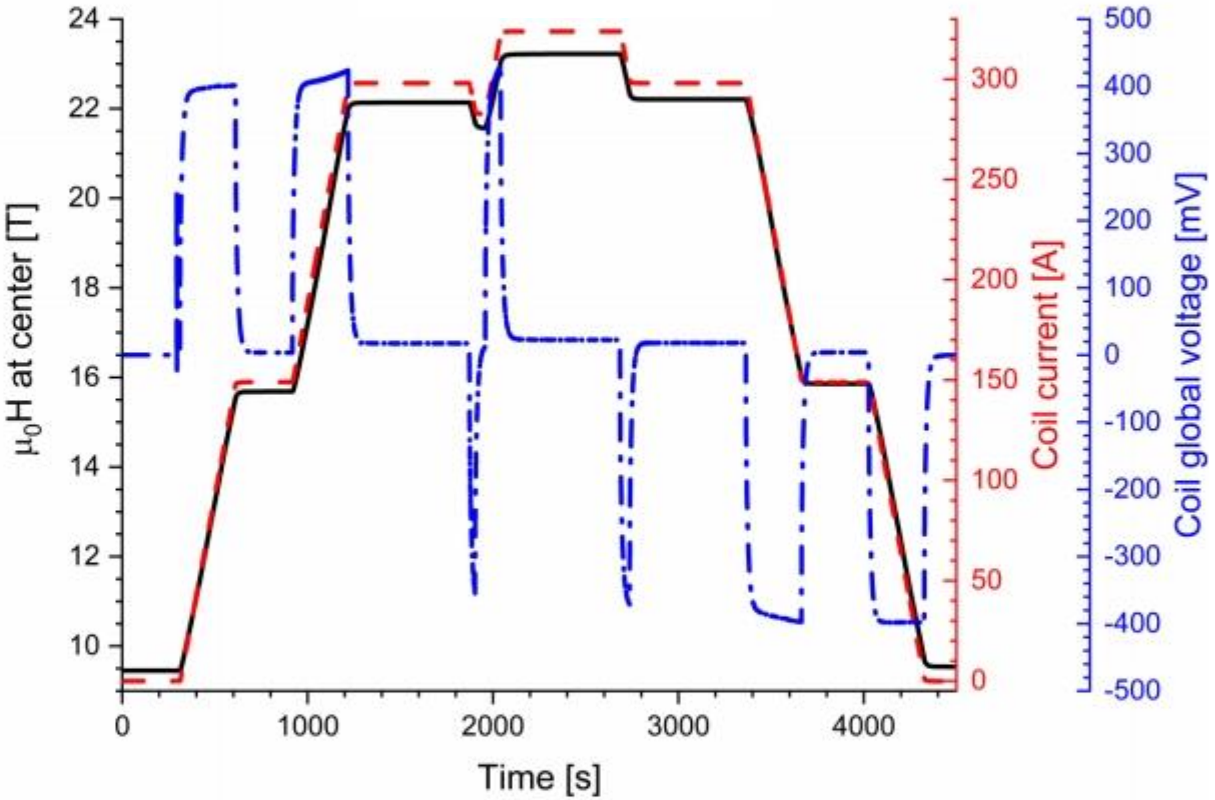


Resistive Outsert



Need to check HTS insert after replacing the broken signals and overbanding !!!!

Estimation of the HTS insert after re-instrumentation



Test results of the MI HTS insert at 4.2 K under B_{ext} = 9.5 T

Time of tests	09/2018	02/2020
I_{coil}[A]	301	323
$\mu_0 H_{resistive}$[T]	8	9.45
Coil Resistance[μΩ]	**7.2**	**70.8**
α[mT/A]	42.4	42.5

→ **No significant damage inside the coil** (no visible bypassing current) → **internal resistance very localized**

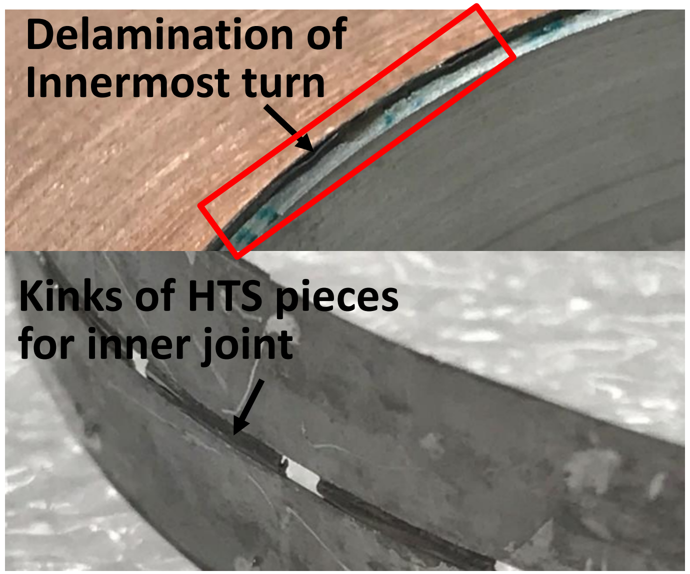
→ **Dissipation too high for test at higher Field !**

?? : **Where is the resistance localized ?**

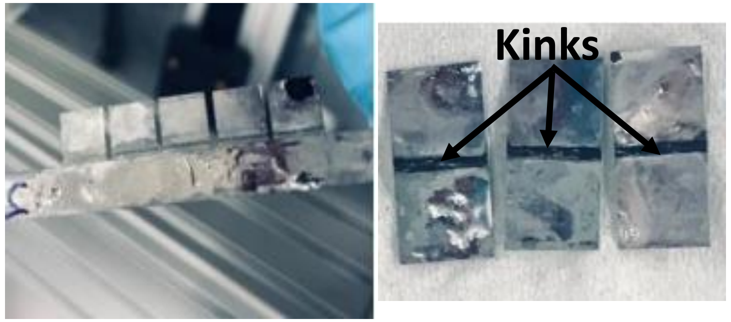
Decided to dismantle the HTS insert

Repair of damaged inner joint and 77 K test of a DP9 - June 2020

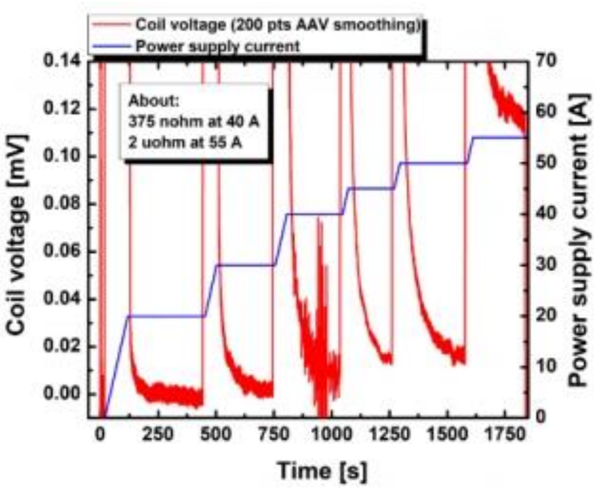
Damaged Inner joints between SP-SP coils



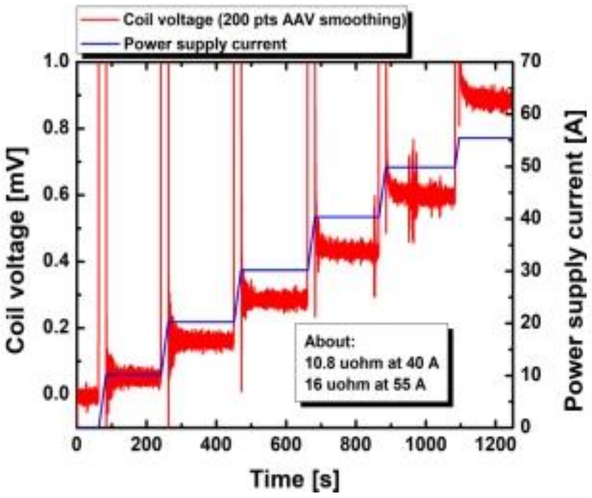
Damaged Outer joints between DP-DP coils



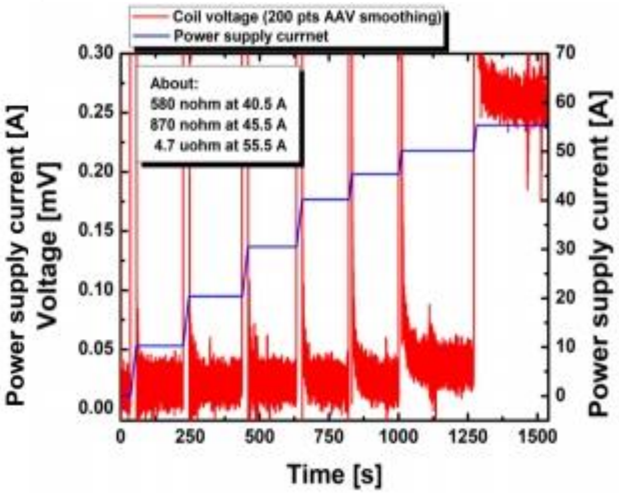
2018 before assembly



2020 after disassembly



2020 after inner joint change



	2018 before assembly	2020 After disassembly	2020 After joint repair
I_c(1µV/cm)[A]	66.7	65.6	65.5
α at center [mT/A]	9.3	9.4	9.4
Resistance at 40 A[nΩ]	**375**	**10800**	**580**

The **resistance of the DP is similar** to that of original one in 2018

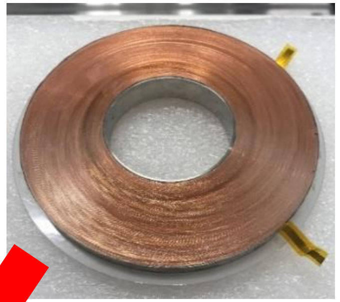
The **field generation presents no change** (measurement accuracy and Screening current effect)

The I_c **value of repaired DP9 is about 1.7% lower** than that of original one.

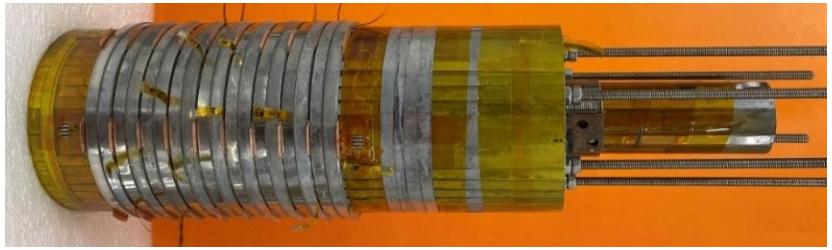
Repairing DP coils and Experimental set-up insert

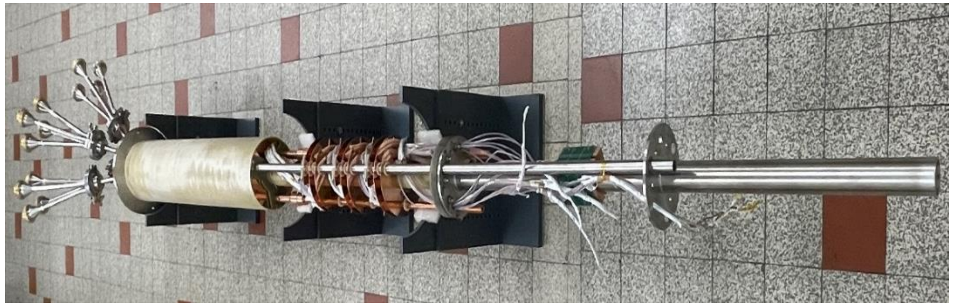
- 7 DP coils (replacement of inner junctions)
- 2 DP coils (replacement of conductor and junctions)
- Sapphire plates inserted in between SP-SP coils

After repair



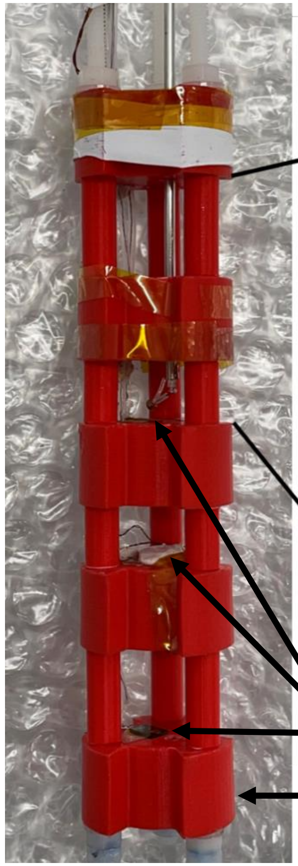
After assembly

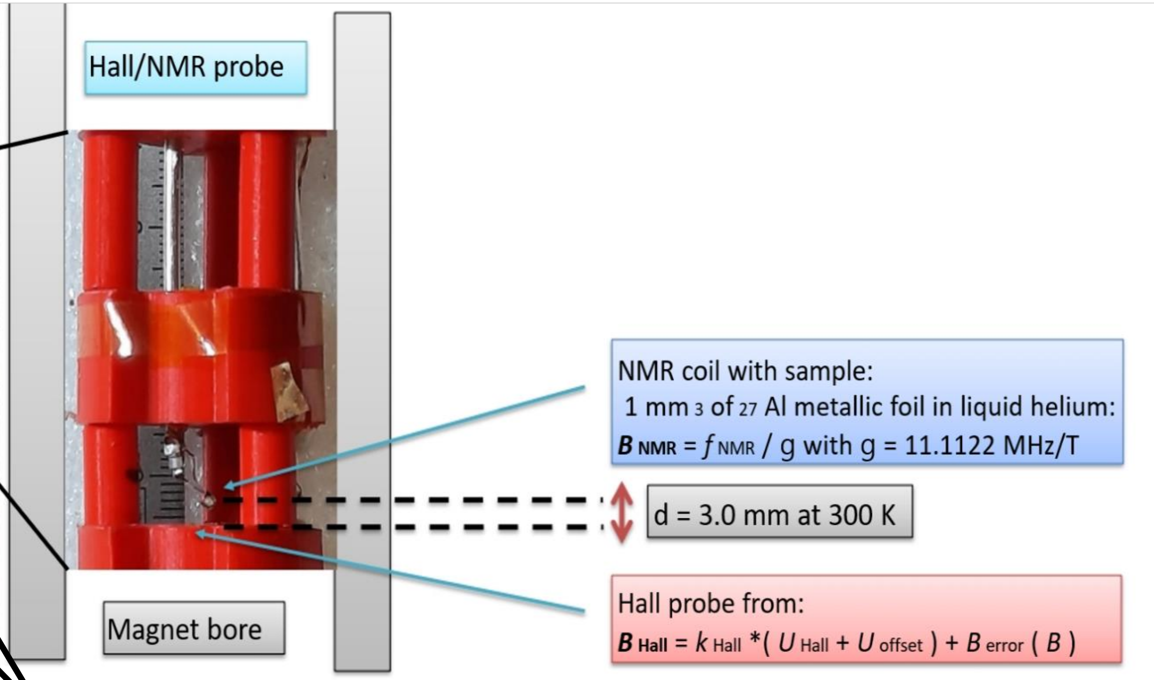




New probe (34 mm sample bore)

Installation of NMR coil and hall sensor for estimation of the MI insert's field homogeneity





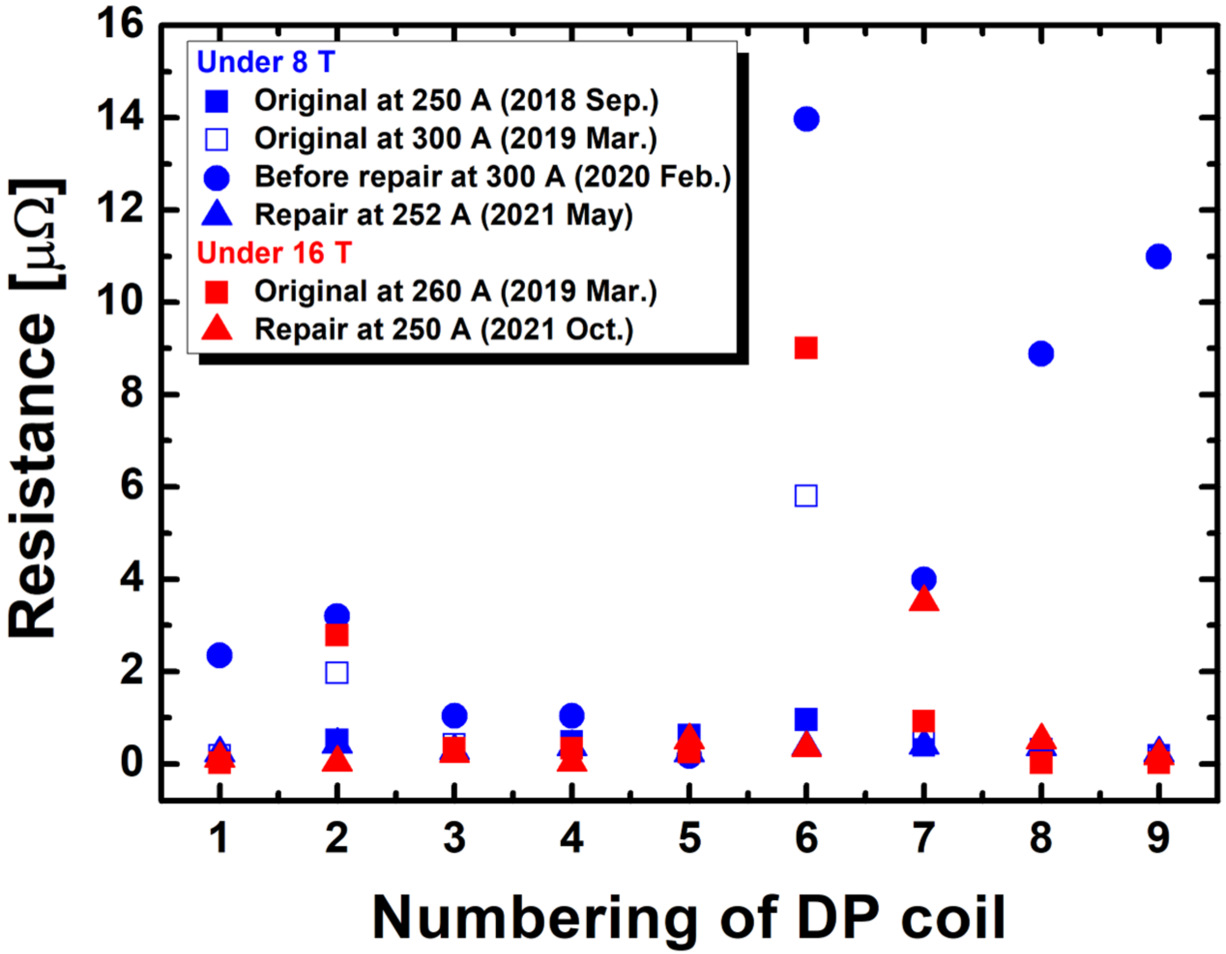
Hall sensors

This holder was located in 34 mm sample bore of new probe

Problems:

NMR and Hall probe are not at the same height: this induces an error term $B_{error}(B)$

Resistance check under B_{ext} = 8 T and 16 T at 4.2 K



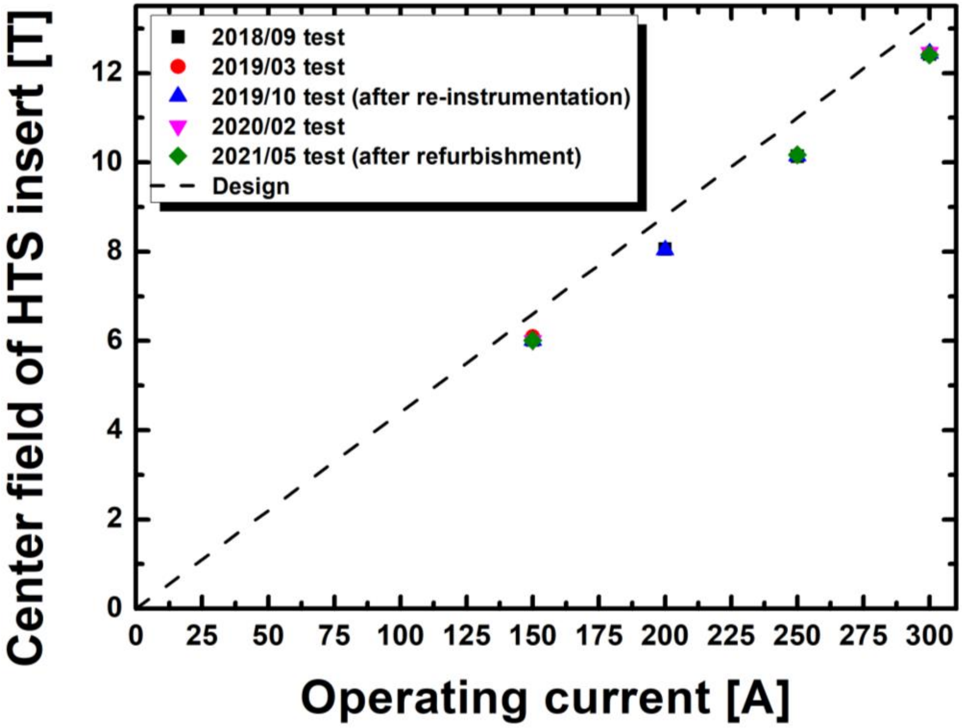
Electrical resistance values of original, dismantled and repaired DP coils under B_{ext}= 8 and 16 T at 4.2 K.

Resistance values at I_{op}=260 (original) and 250 A (repaired) under B_{ext}=16 T

DP No.	Resistance [μΩ] (Original DP)	Resistance [μΩ] (Repaired DP)
1	0.17	0.23
2	2.7	0.22
3	0.34	0.31
4	0.34	0.19
5	0.24	0.51
6	9.0	0.36
7	0.92	3.51
8	0.17	0.51
9	0.18	0.23

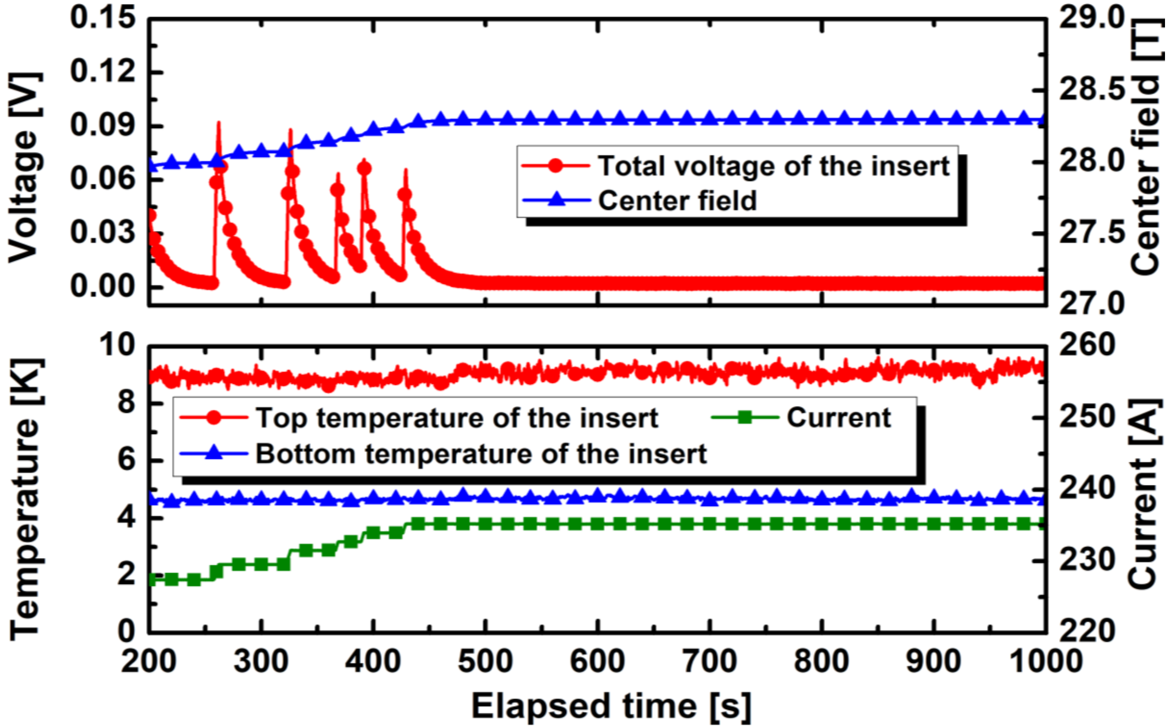
Field production performance

Standalone HTS



Center field of the HTS insert with various I_{op} in SF at 4.2 K

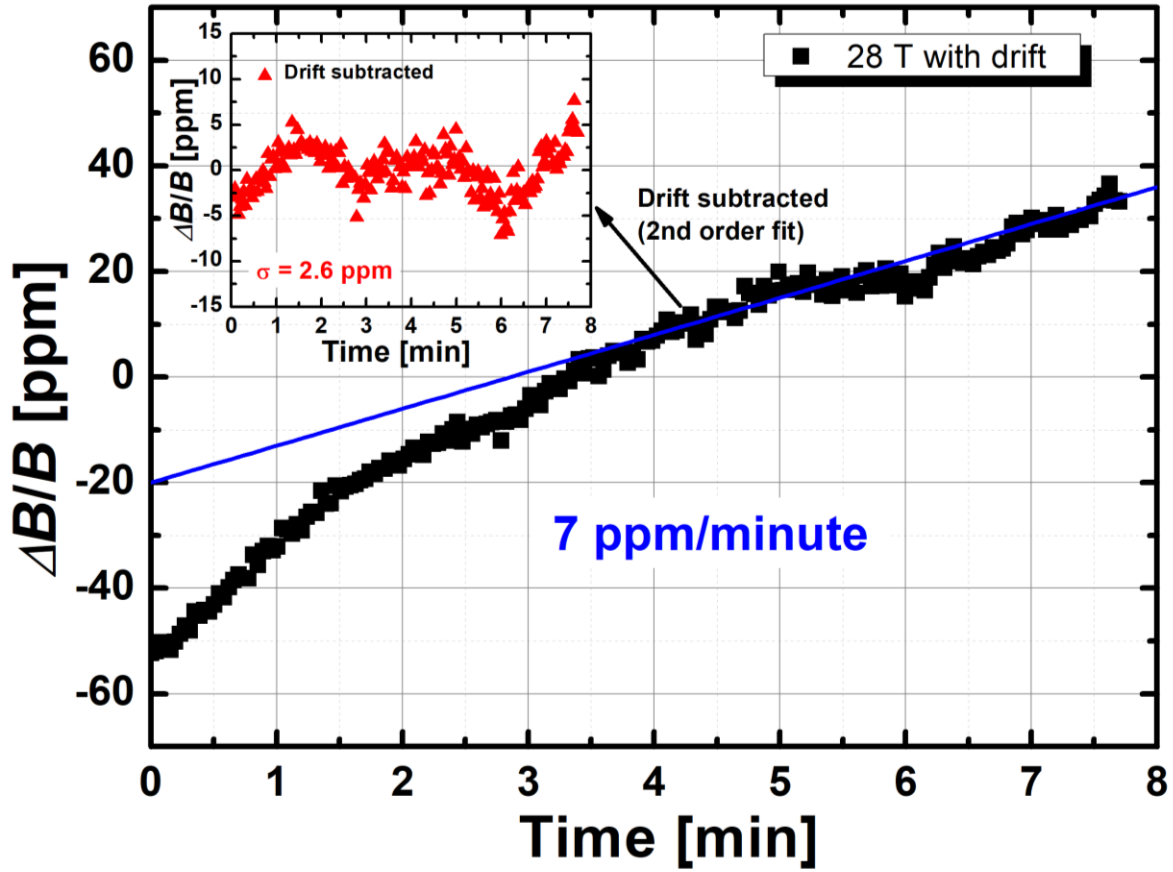
Hybrid: Resistive + HTS



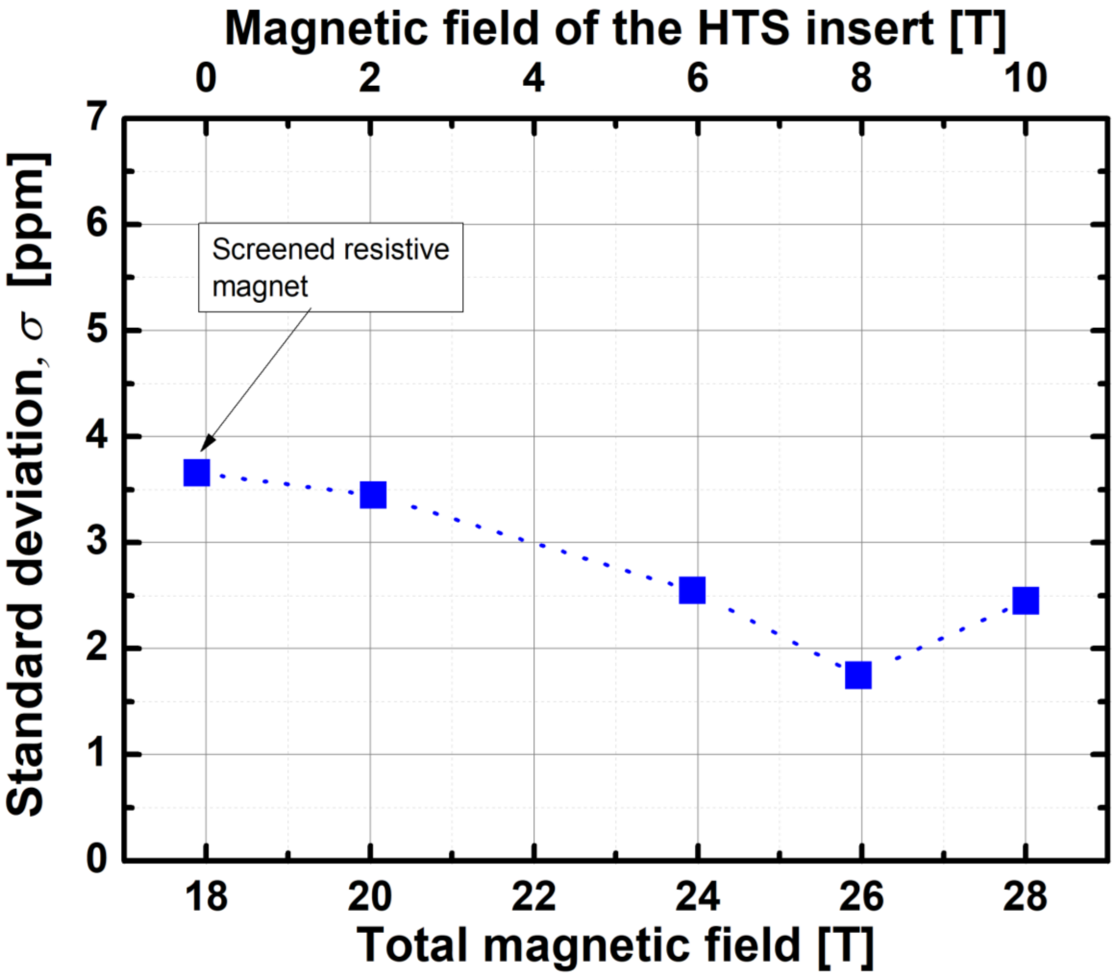
Charging test results of the repaired MI insert under B_{ext} of 18 T

- Field production performance of the original and repaired inserts were almost same in all cases.
- Even before the insert was repaired, field production performance was not changed.
  (Winding was not damaged, no-bypassing current)

Estimation field draft and fluctuation via NMR

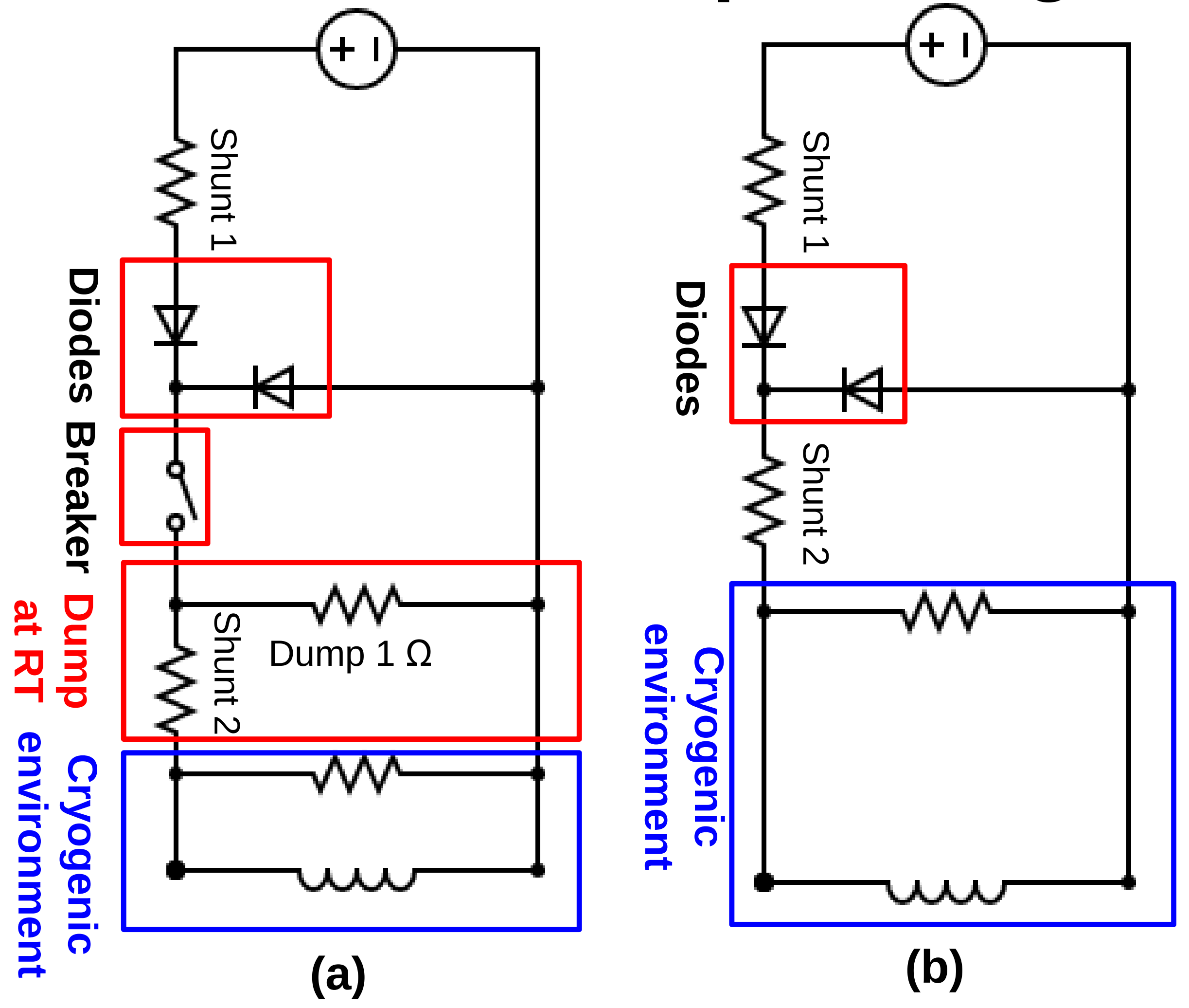


Δ*B*/*B* measured NMR as function of time at B_{tot}= 28 T at 4.2 K

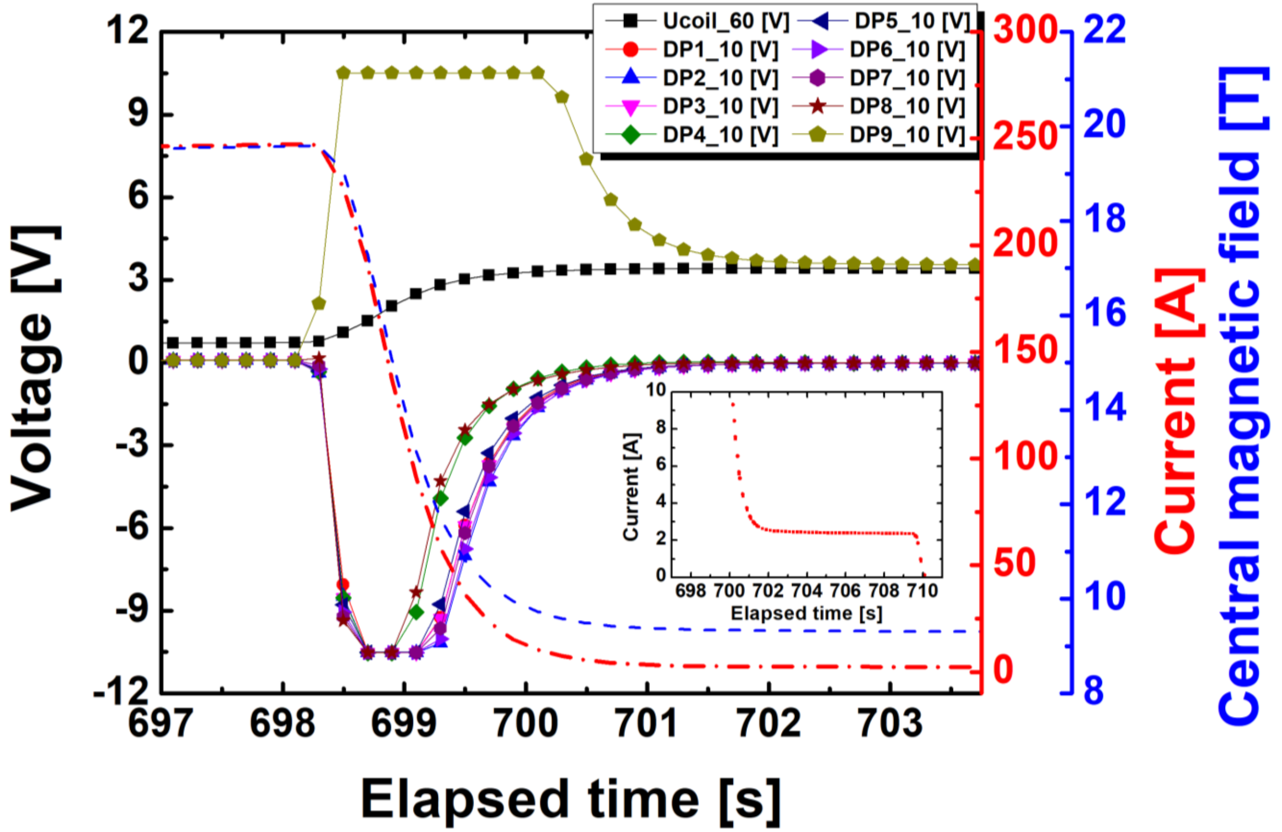


σ values of field fluctuation subtracted from 2nd order fit of results as function of B_{tot}

Protection technique using MI winding and PS limitation



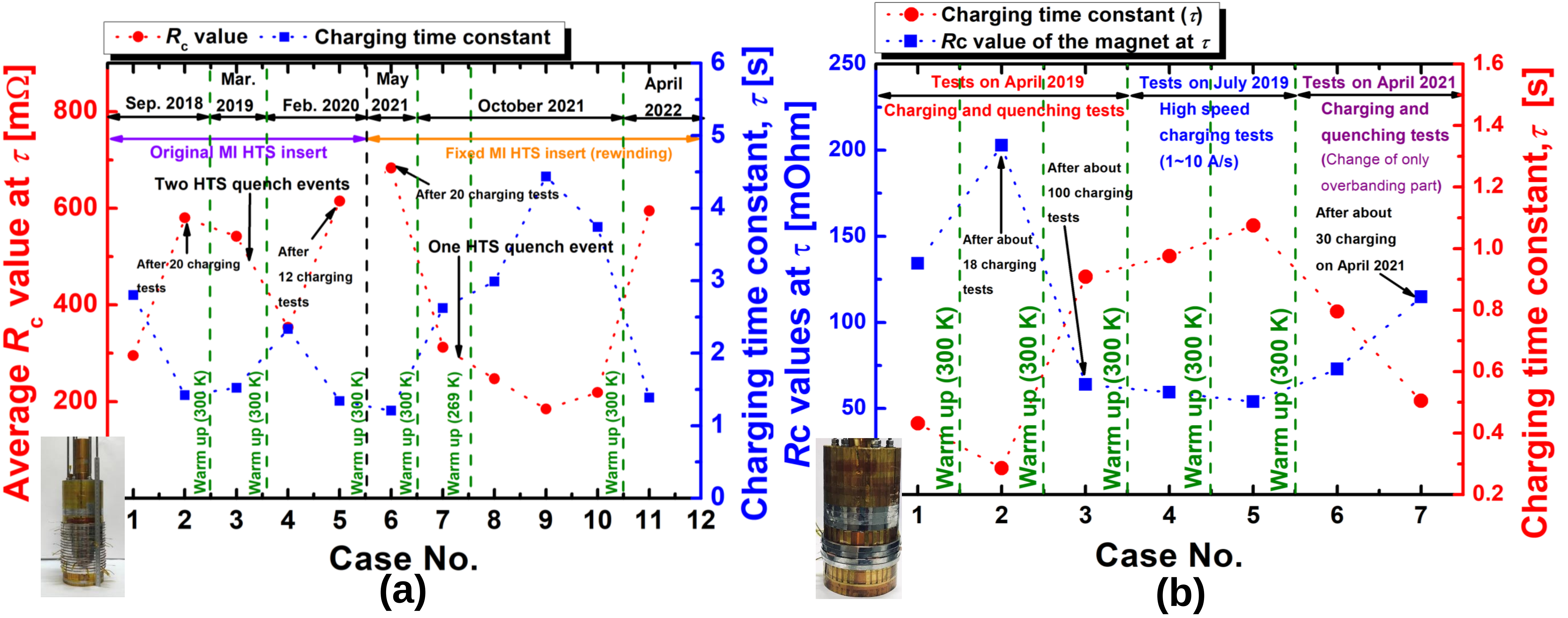
Protection circuit diagram of the MI insert: (a) previous tests; and (b) present tests



Power supply voltage limitation : 3.5 V

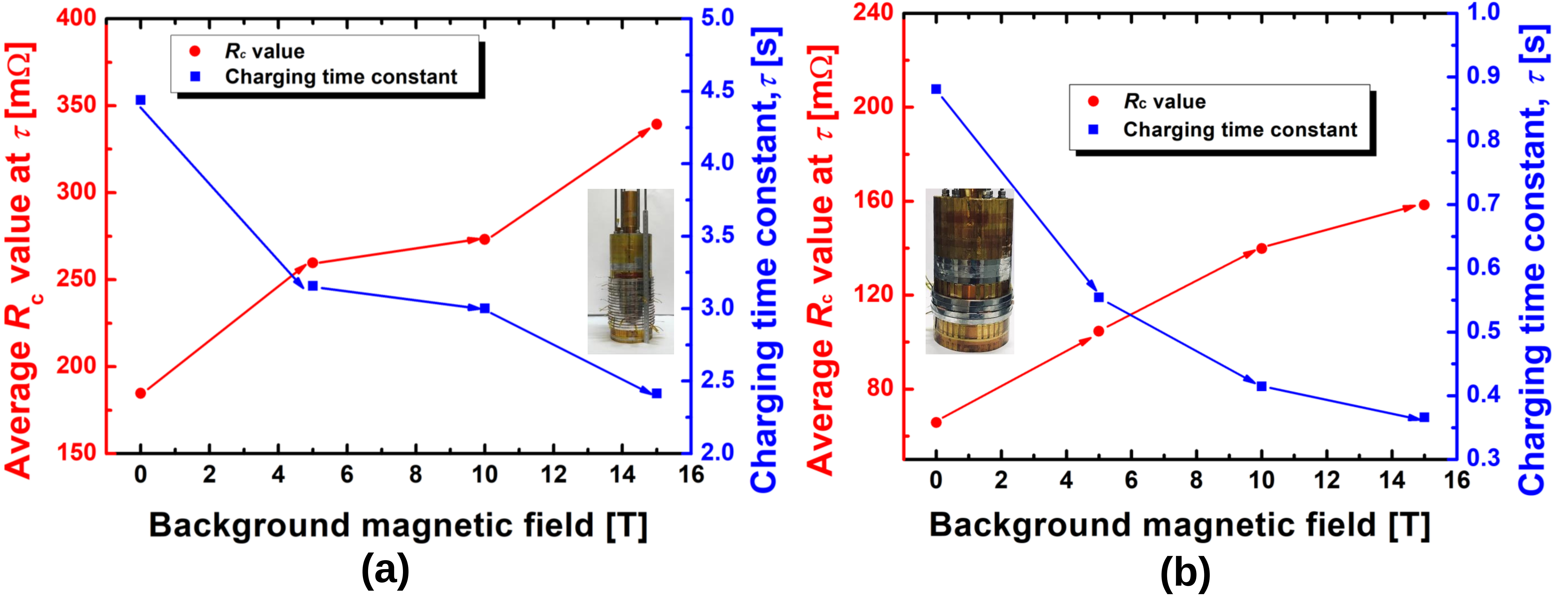
Quench behaviors of the MI insert at I_{op} = 247 A under 9 T at 4.2 K without switch and dump resistor (Test on April 2022)

R_c change of the two MI magnets in self-field at 4.2 K



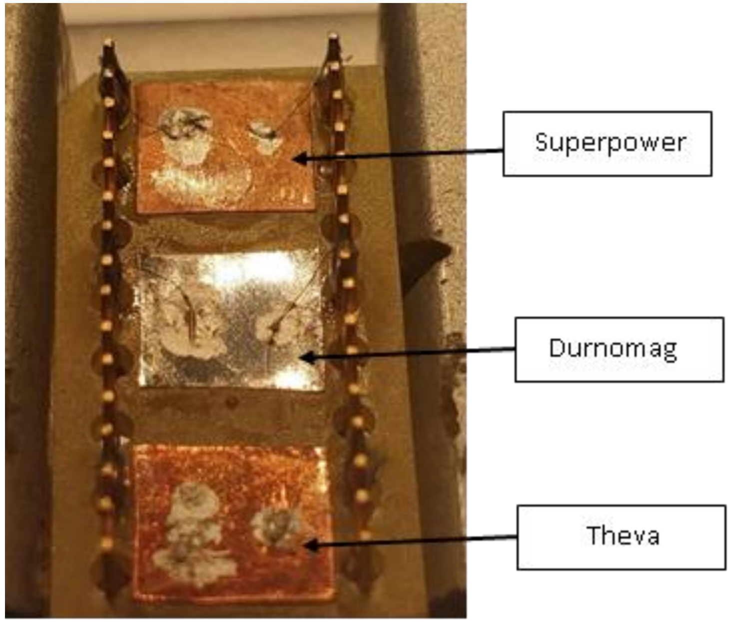
The measured τ and estimated R_c values of MI magnets in SF at 4.2 K: the NOUGAT MI insert (a); and the Theva-SuperPower magnet (b).

R_c change of the two magnets under various B_{ext} at 4.2 K

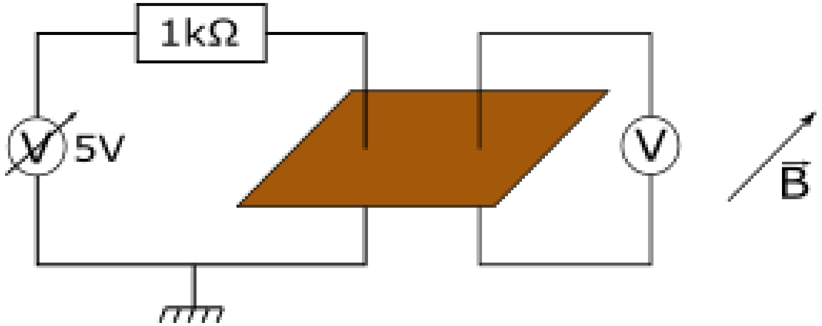


The measured τ *and* estimated R_c values of the MI magnets at background fields of 0, 5, 10, and 15 T at 4.2 K: The NOUGAT MI insert (a); and the Theva-SuperPower magnet (b).

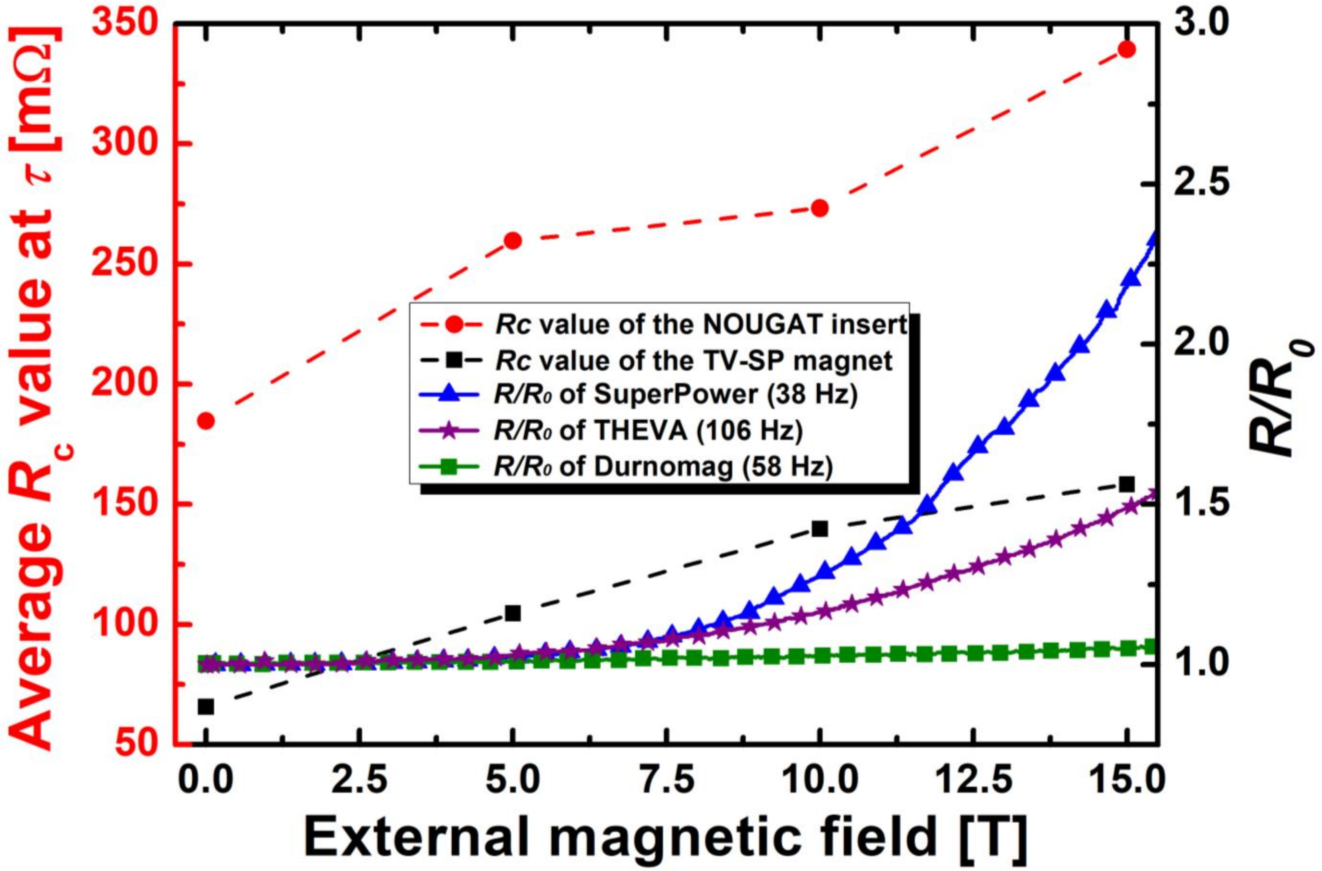
Magneto-resistance of REBCO and Durnomag tapes at 4.0 K



The holder with samples for measuring MR



Electrical scheme for measurement of MR



R_c of the MI insert and normalized resistance of REBCO and Durnomag tapes from B_{ext} = 0 to 15 T

Summary

Metal insulated HTS magnet showed

- very fast charging/discharging time
- self-protecting feature against quench events under high magnetic field
- good field stability (field drift: 7 ppm/min and field fluctuation: 2.6 ppm) with resistive magnet
  Note the NMR record started immediately after reaching the target field
- possibility of simple protection only using power supply limitation

For high field MI HTS magnet, we need to

- develop electrical junction techniques of high mechanical strength against repetitive high magnetic pressure and quench events
- make stable cryogenic environment without trapped helium bubble at magnet area
- obtain exact range of characteristics resistance

For SuperEMFL and FASUM projects,

- four HTS model magnets wound with various recent REBCO tapes will be tested to estimate electrical/mechanical properties and our joint/assembly techniques under very high magnetic fields


Thank You !
Question ?