Alternative Approach to ReBCO HTS Magnet Operation and Protection:

- Influence of Turn-to-turn Equivalent Resistivity and Coil Size on Fast-discharge and Ramping of Metallic Insulation HTS Coils

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FRIB

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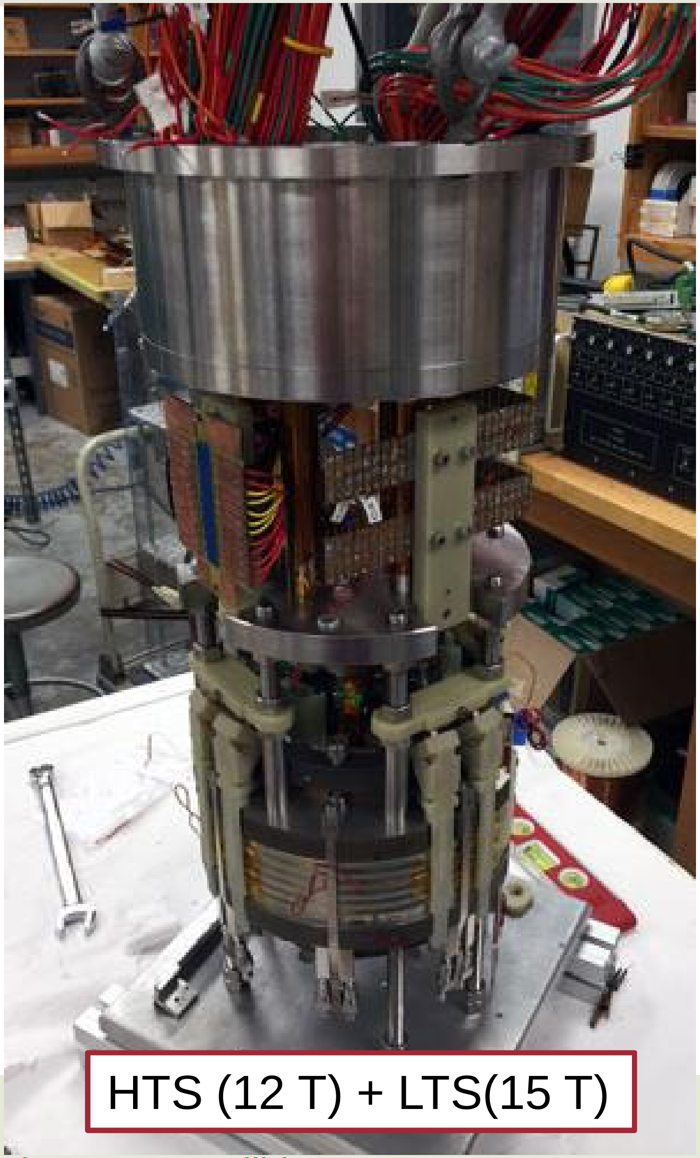
MagLab Claims Record with ReBCO Superconducting Magnet



This ReBCO test coil helped the MagLab set a new world record for superconducting magnets: 27 Tesla.
10 June, 2015

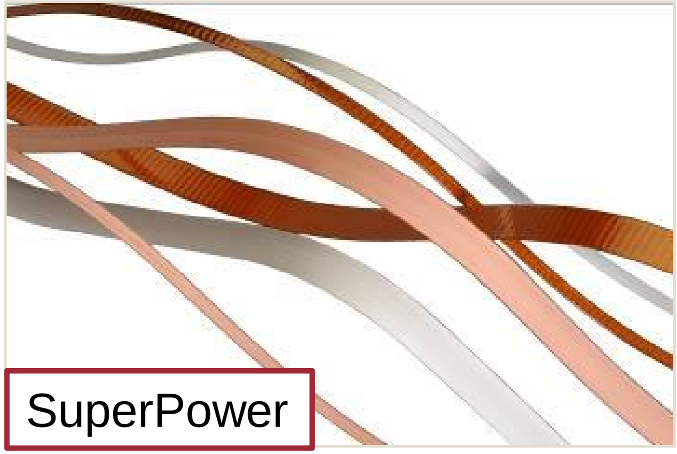
NATIONAL HIGH MAGNETIC FIELD LABORATORY

Outline

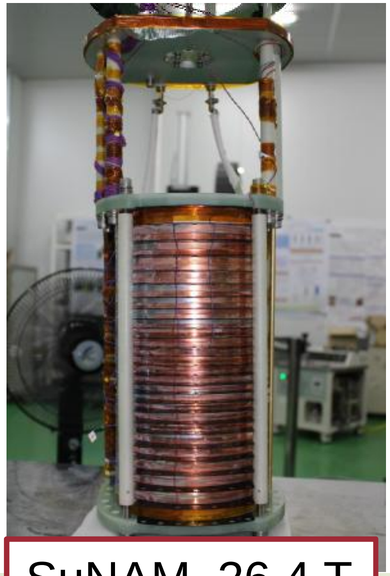
- Introduction
  - Traditional Insulation
  - Metallic insulation (Stainless steel or Cu insulation)
- Development of small-scale Stainless steel insulated HTS coil
  - Coil design, winding, testing
  - Fast-discharge experimental results and analysis
  - Equivalent resistivity calculation
- Prediction of ramping behaviors of large-scale HTS coils
  - Dependence of ramping rate, coil size, equivalent turn-to-turn resistivity…
- Two applications
  - Multiple small-diameter coils for NMR applications
  - Large coils for accelerator and induction heater applications

ReBCO Conductor (2G) HTS Coil

- Rare Earth-based, **second-Generation High-Temperature Superconductor wire**
  - Robust wire characteristics due to Hastelloy substrate
  - Wide temperature range (4K<T<65K)
- **HTS Coils**
  - React & Wind
  - Flexibility in coil winding
  - Suitable for a wide variety of applications: energy, industrial, science & research, military & defense, transportation


SuperPower


MAGLAB, 27 T


SuNAM, 26.4 T

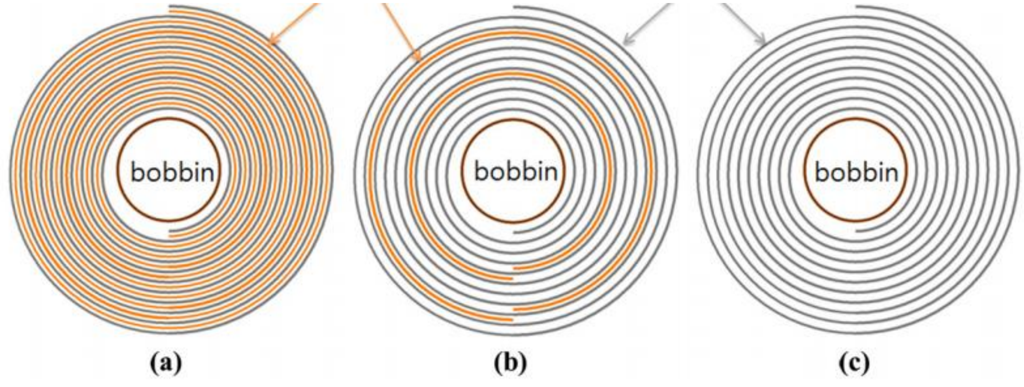
Challenges in HTS Magnet Protection and Operation

- Voltage across normal zone is too small to detect (Earlier quench stage)
- Normal zone propagation in HTS too slow (Quench)
- Most available test data based on short sample, small coil
  - Large # of stacked HTS coil for NMR (10 – 20 coils), few test data available
  - Large-scale HTS coil for accelerator dipole or induction heater, no test data available
- Traditional detect-quench-protection approach does not seem to work for the HTS magnet → Alternative approaches
  - Novel winding
  - Better understanding
  - Systematic modeling and simulation
  - Prototyping and extensive tests
  - Great care

Metallic-Insulation HTS Coil and Its Winding

- Traditional insulation used in LTS superconductor wires, Kapton, Fovar
  - Recently proposed ZnO dope polyimide insulation
  - HTS normal zone propagates still slow (~cm/second)
  - High risks for large-scale magnets
- Metallic strip insulation
  - No turn-to-turn insulation, conductors are wound directly
    - » Cu/Cu contact, (even soldered Cu)
    - » Soldered Cu/Cu contact
  - Co-wound with metal strips
    - » Cu strips, similar to the No-insulation contact, but two contact layers
    - » Stainless steel strips, high resistivity

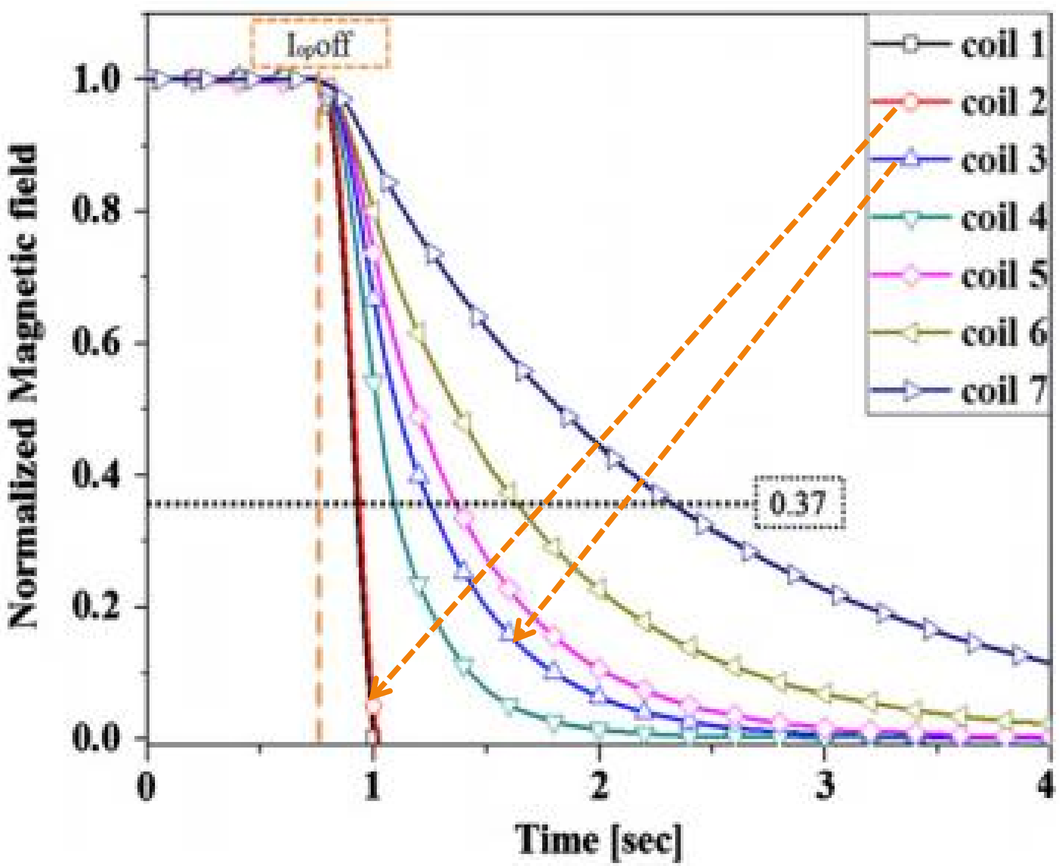
Metallic strip insulation



Supercond. Sci. Technol.27(2014) 06501

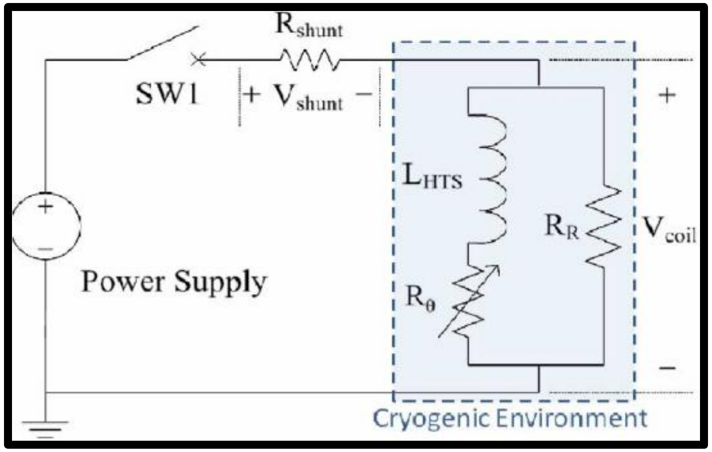
Fast-discharge Behaviors of HTS Coil
Stainless Steel Insulation Coils Needs More Detailed Studies

Supercond. Sci. Technol.27(2014) 06501



Co-wound material

Kapton,	every turn
SS,	every turn
Cu,	every turn
Kapton,	every 4 turns
SS,	every 4 turns
Cu,	every 4 turns
Kapton insulation	

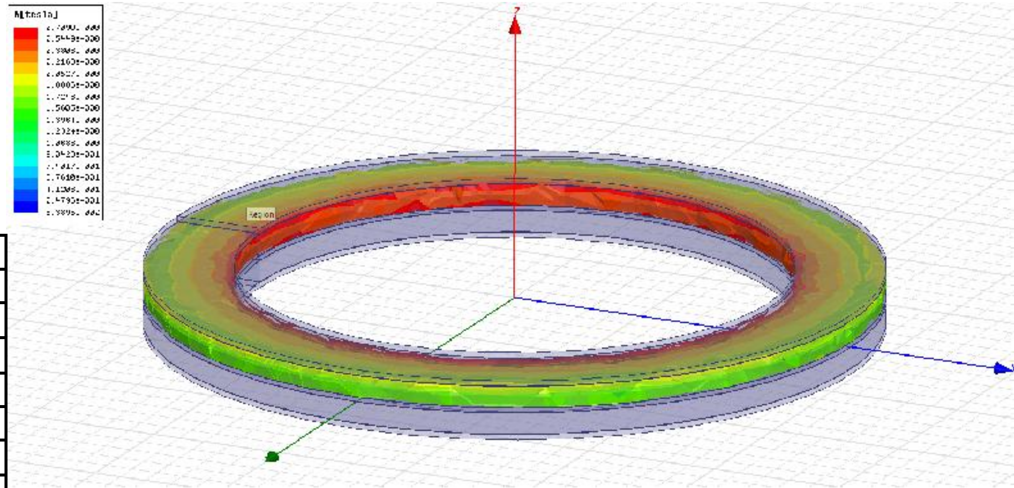


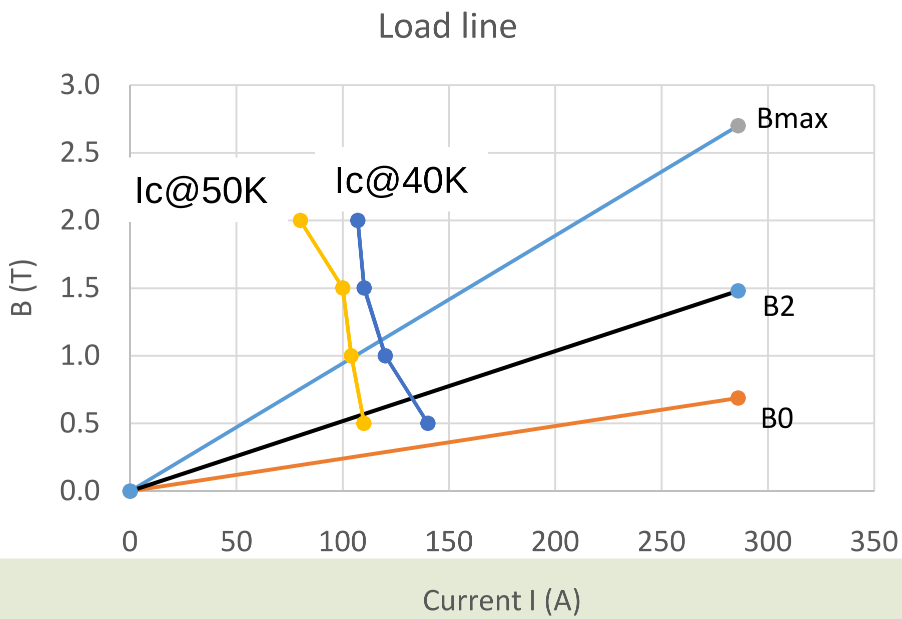
Kapton Insulation = SS Insulation? (NO)

Stainless Steel Insulated HTS Coil - Coil Design

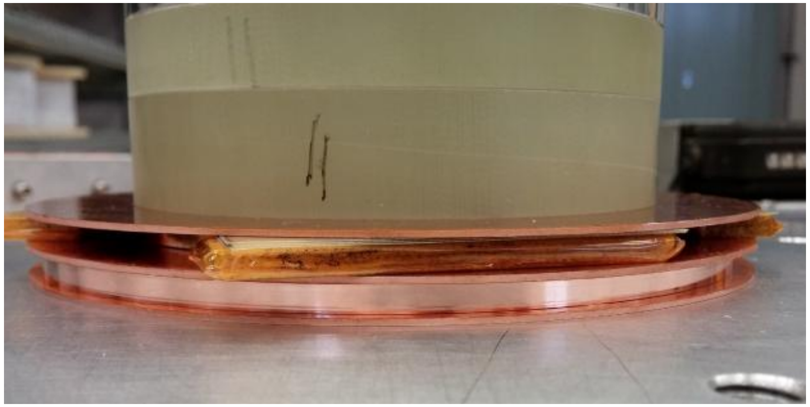
Double Pancake Coil (DPC) Co-wound with SS strips

a1 (ID/2)	**50.8**	mm
a2 (OD/2)	**67.31**	mm
Conductor		
Thickness	0.1	mm
Width	4	mm
SS		
Thickness	0.025	mm
Width	4.2	mm
Cell (conductor + SS)		
Thickness	0.125	mm
Width	4.2	mm
Cross section	0.525	mm2
Coil		
ID	101.6	mm
OD	134.62	mm
Coil volume	25729.6	mm3
Total conductor length	49008.7	mm
	49.00	m
Total turns	132.08	

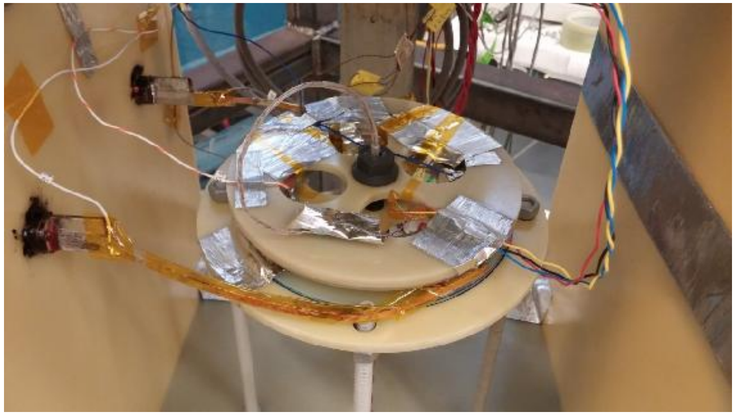




Stainless Steel Insulated HTS Coil - Coil Winding and Testing

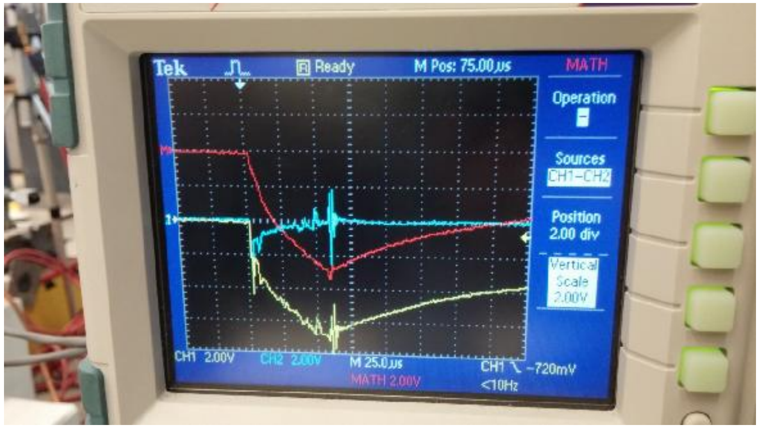


HTS Coil Winding



HTS Coil Instrumentation

Splice Fabrication



Fast-discharge Tests
(No dump resistor)

Stainless-Steel Insulated Coil VS Cu Insulation Coil

Table 1. Specifications of thetest ReBCO tapes

Supercond. Sci. Technol. **28** (2015) 045017 (9pp)

Parameters	Tape1	Tape 2	Tape 3
Thickness	0.1 mm	0.3 mm	0.25 mm
width	4.0 mm	4.75 mm	4.2 mm
Lamination	*Electroplated Cu*	Copper/Solder	Brass/Solder
Co-wound strip	SS	*No*	*No*
Substrate	Hastelloy	Hastelloy	Hastelloy
I_c @ 77K, tape	140 A	220 A	170 A

Table 2. Specifications of thetest NI coils

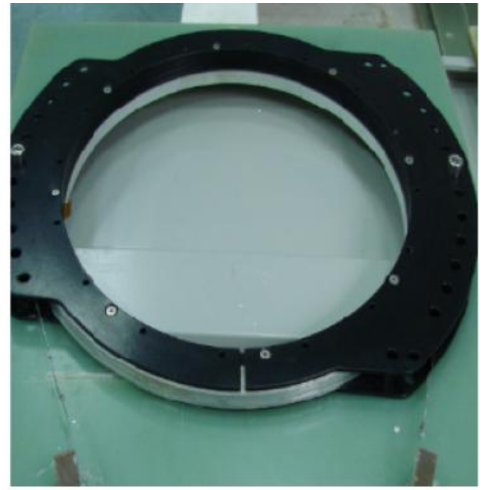
Parameters	Coil 3	Coil 2	Coil 1
Coil type	DP	SP	DP
Tape	Tape 1	Tape 2	Tape 3
Number of turns	130*2	27	62*2
Inner diameter	102 mm	100 mm	245 mm
Tension	~5 kg	7 kg	4 kg
Total length of wire	98 m	9.1 m	101 m
Inductance, L_{coil}, *cal.*	12.1 mH	150μH	8.11 mH
B_z per amp, *cal.*	2.64 mT	0.3 mT	0.59 mT
I_c, coil @77K	~120A@40K	133A@77K	97A@77K

Stainless-Steel Insulated Coil VS Cu Insulation Coil

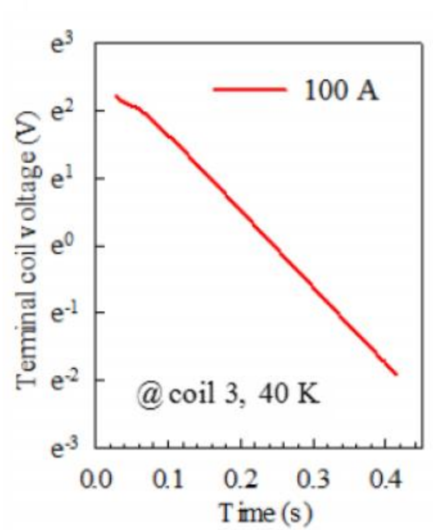
Fast-discharge *V*(*I*) Curve → Time constant *τ* → Equivalent ρ

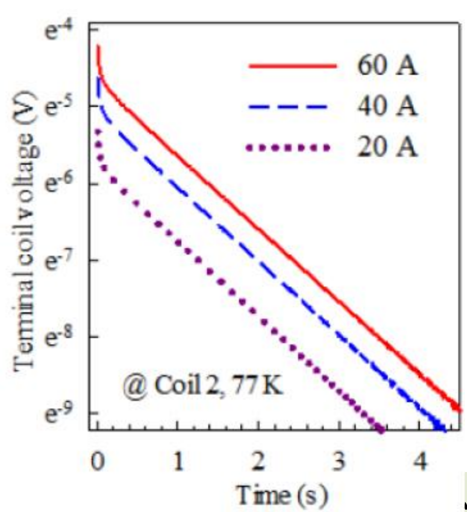
Coil 1 (SS Insulated)

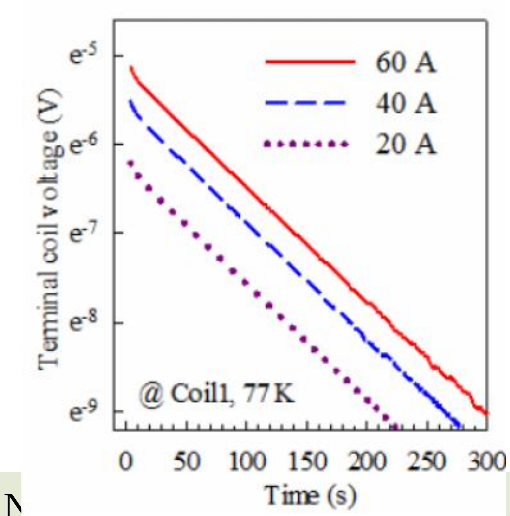
Coil 2 (Cu)



Coil 3 (Brass)





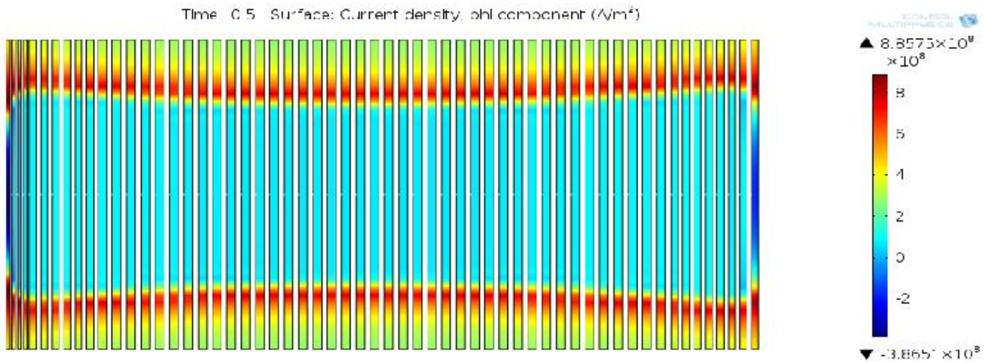


Equivalent Contact Resistivity
Coil 1 (SS)
7469 μΩ·cm^2
Coil 2 (Cu)
27.5 μΩ·cm^2
Coil 3 (Brass)
88.0 μΩ·cm^2

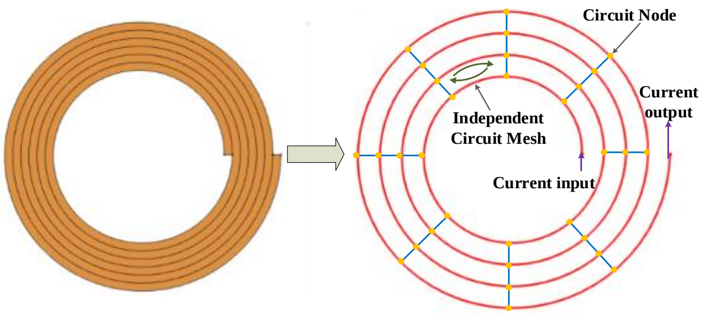
~100 times more

Ramping Behaviors of Metallic Insulation HTS Coil

- Benefits of contact resistance for fast-discharge protection becomes disadvantage during charge ramping
- To clarify one of the most critical concerns → Will the metallic insulation HTS coils have settle-off problems?
- Apply equivalent insulation resistivity from small coils → predict ramping behaviors in larger coils
- HTS coil modeling – a hybrid modeling (<u>Critical State</u> + <u>Metallic Insulation</u>)



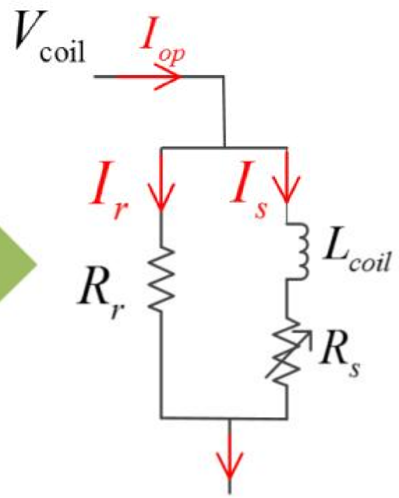
2D Critical State Current density profile

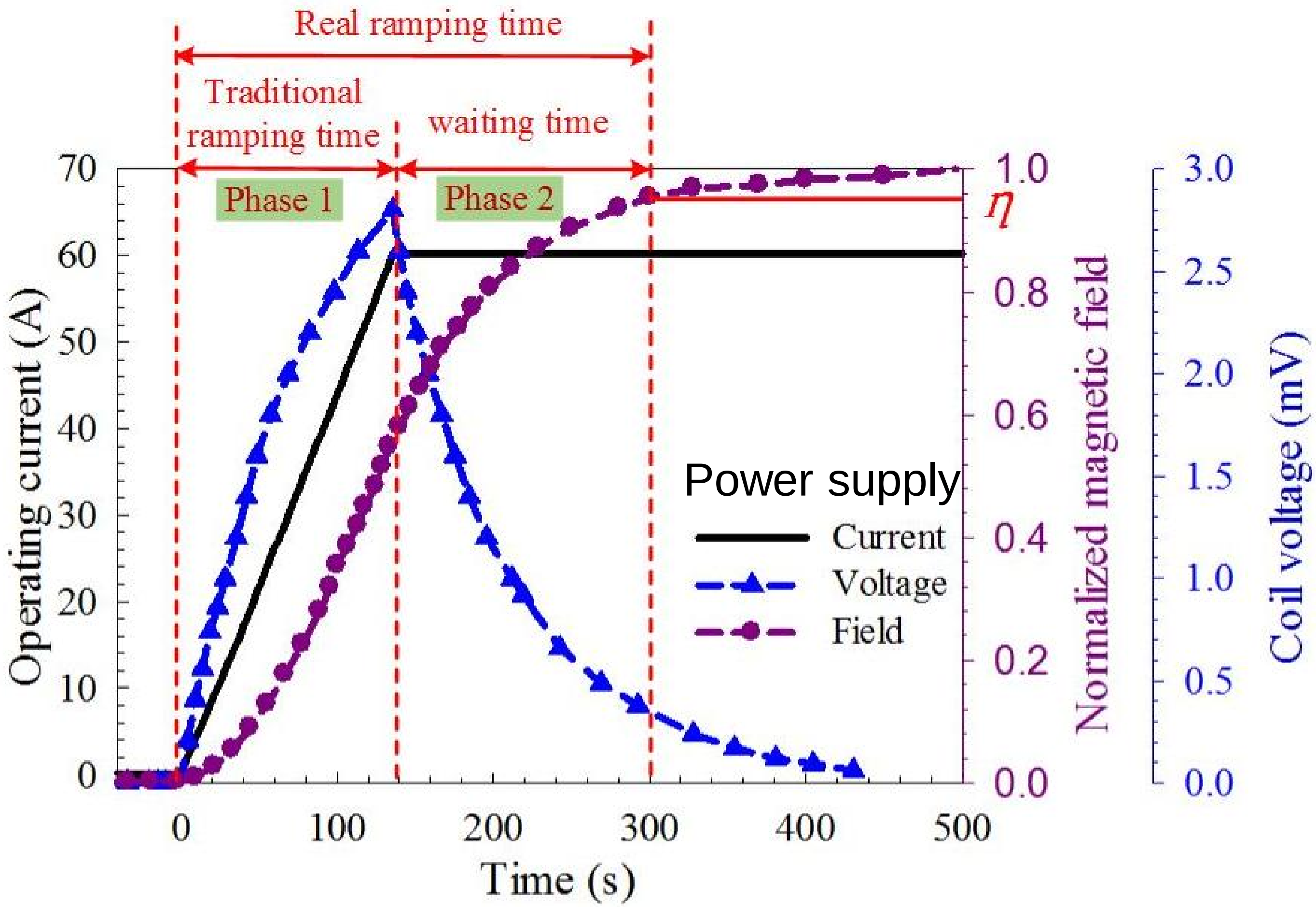


Equivalent circuit grid model

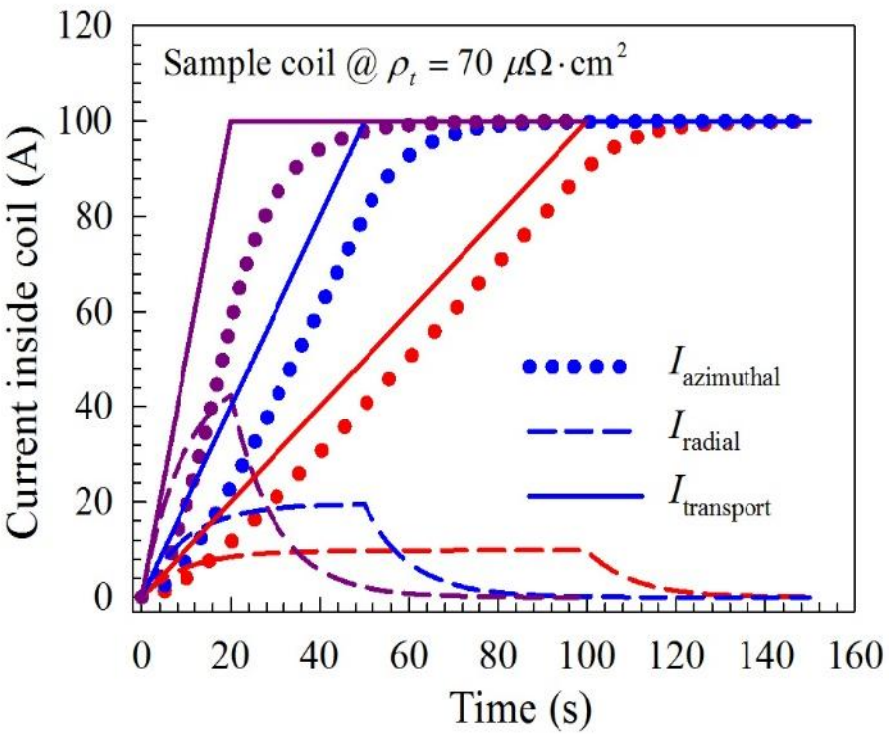
Ramping Behaviors Characterization in Metallic Insulation HTS Coils

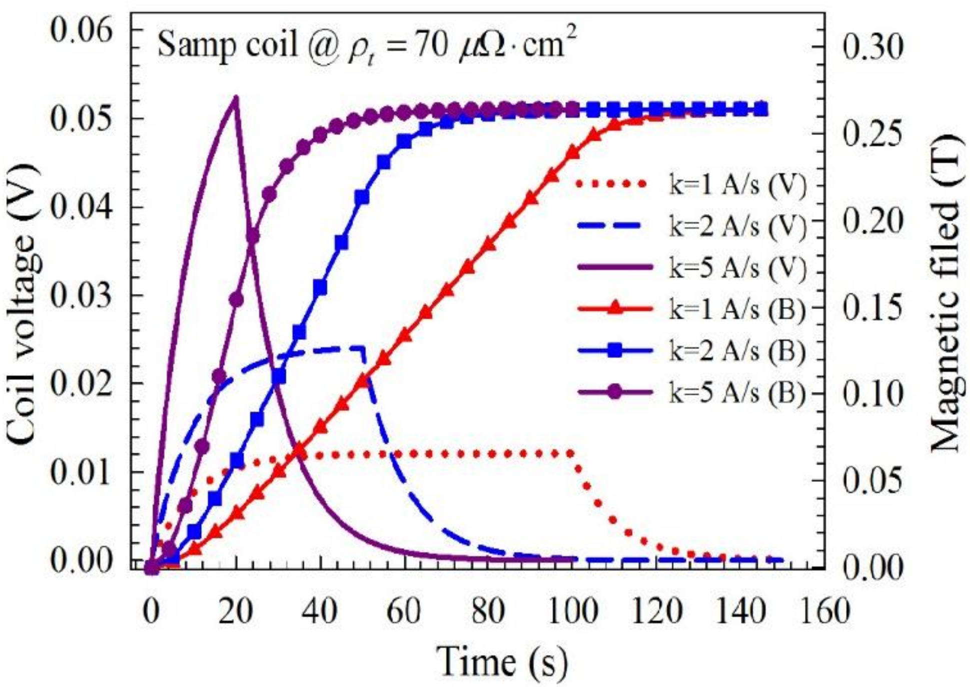
- Magnetic field *B* lags coil zzimuthally flowing current!





Dependence of Ramping Rate if ρ = 70 μΩ·cm²
(Typical Cu Strip Co-Winding)





Current vs Time

$I_{transport}$: total power supply current

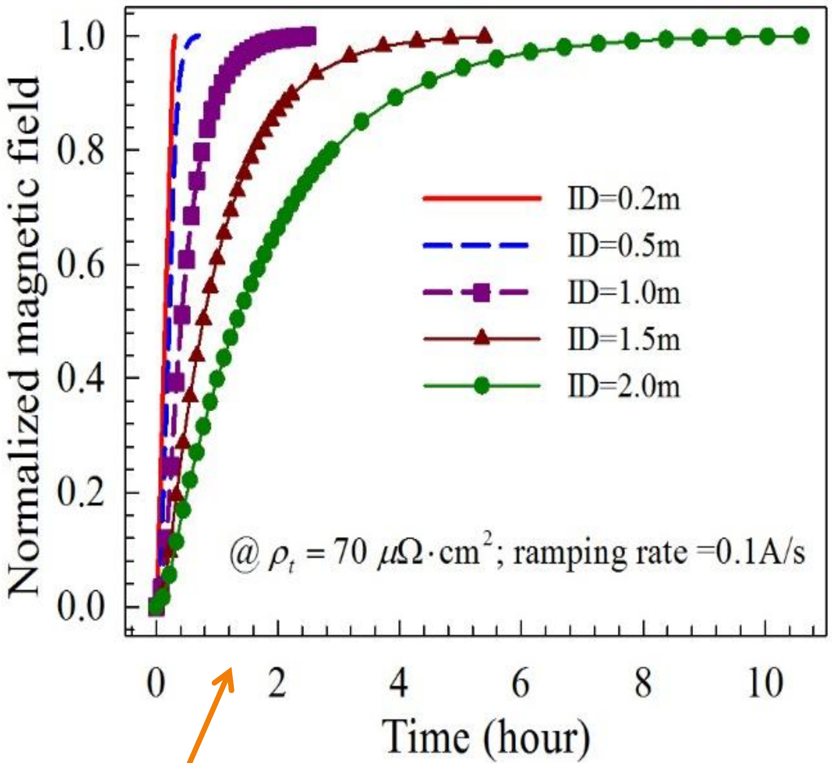
$I_{azimuthal}$: current along length

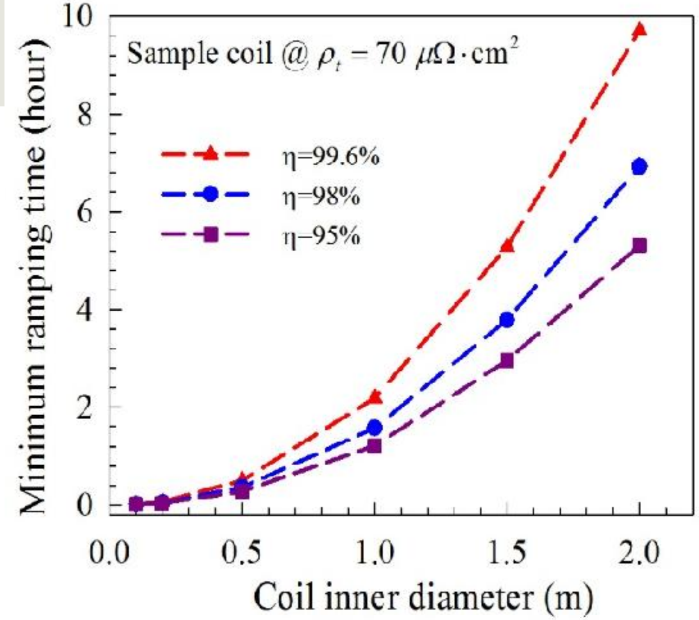
I_{radial}: current along radius

Coil Voltage vs Time

→ Field lags the current

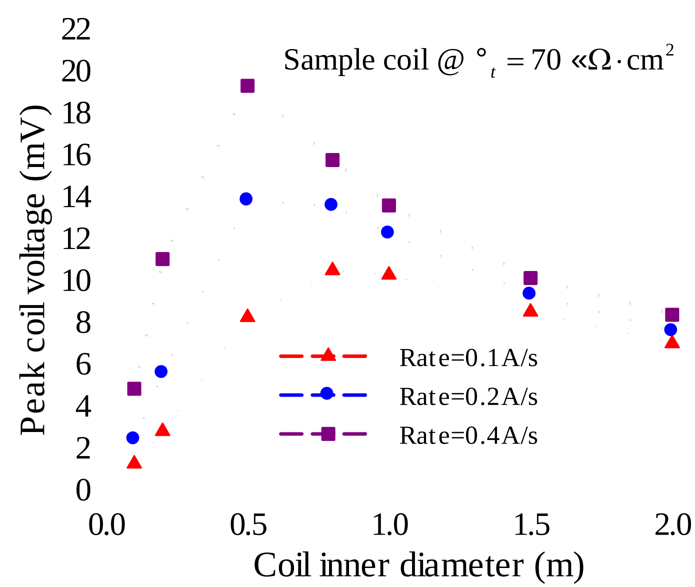
Diameter Becomes Larger…



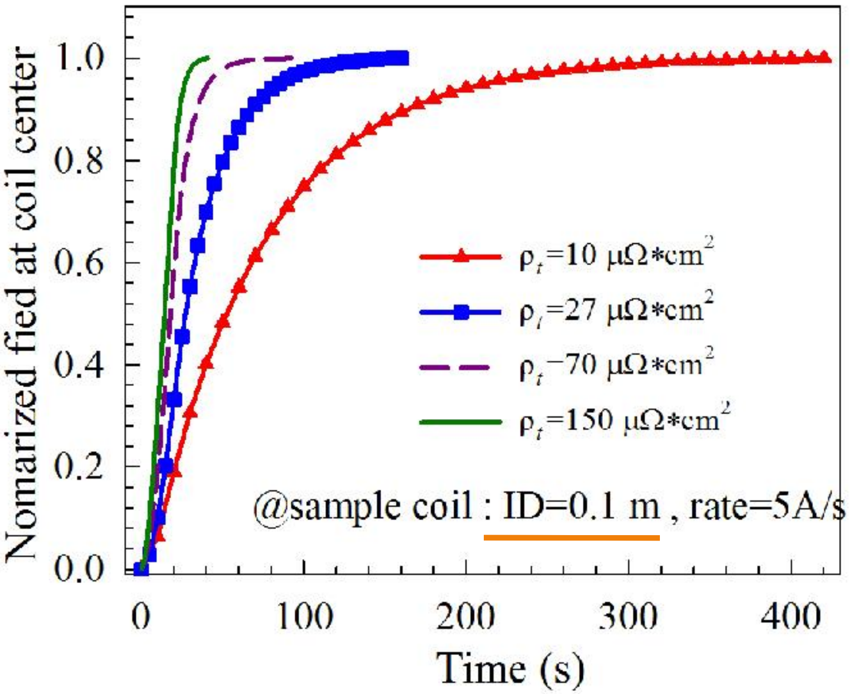


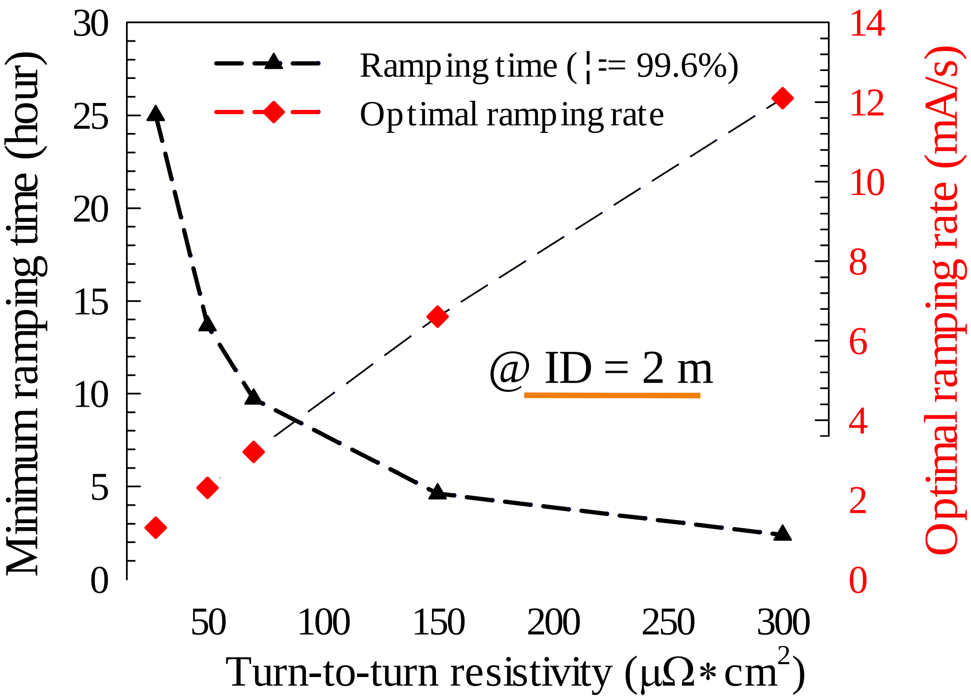
B(t) for Different Diameter Coils

Required Ramping Time VS Coil Diameter



Influence of Turn-to-turn Resistivity

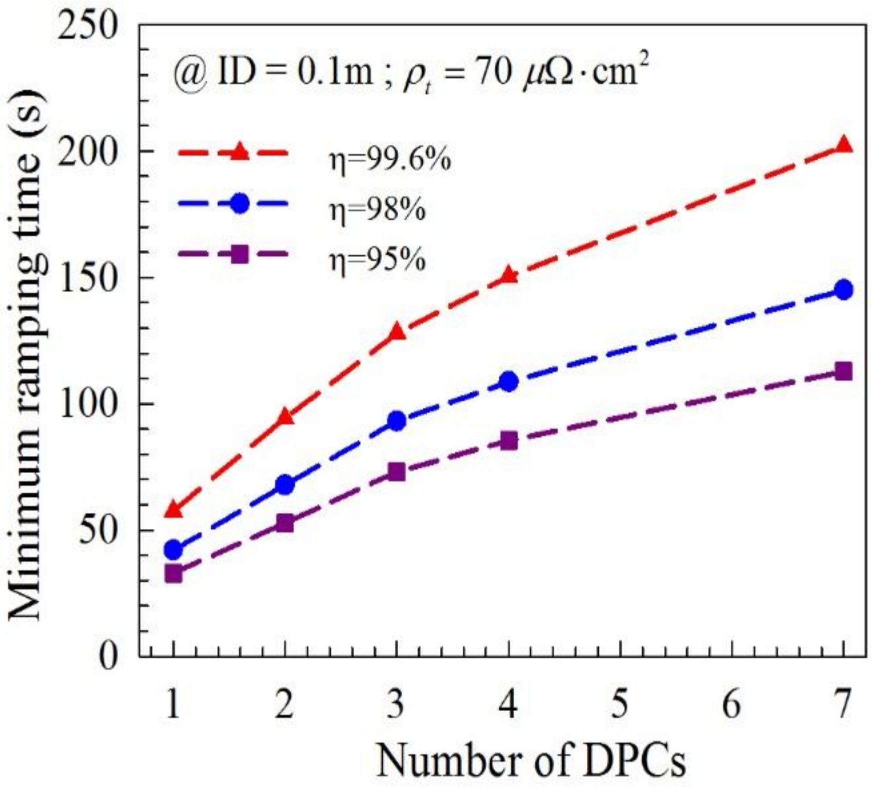




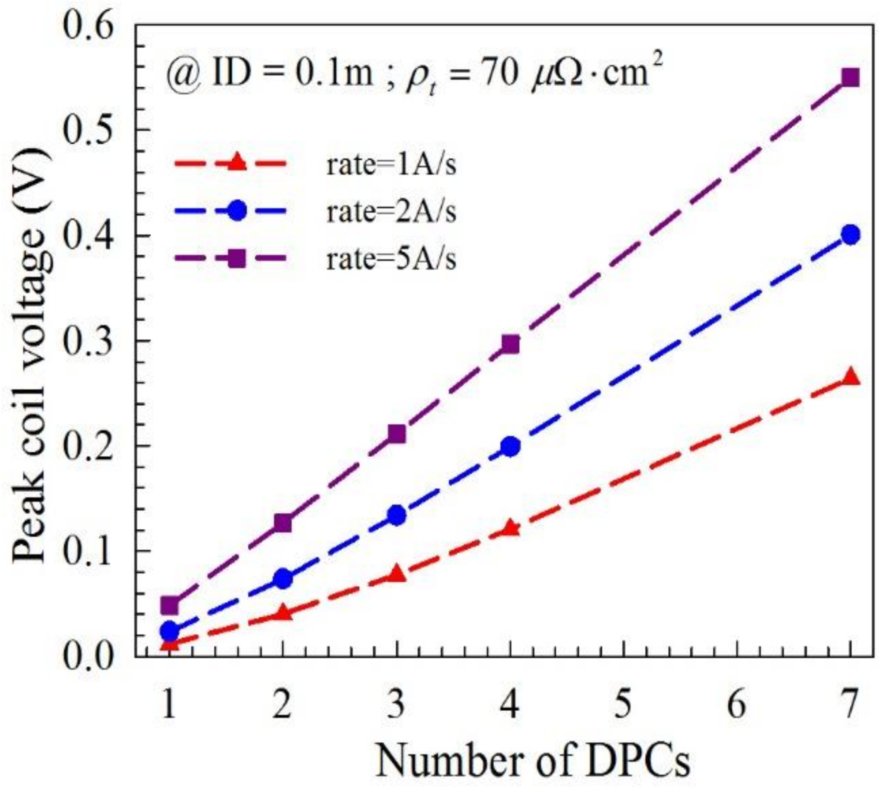
For smaller coils ID=0.1 m, increasing equivalent resistivity reducing ramping time, but the maximum time is ~ 400 s.
→ Cu insulation may be OK for 0.1 ID coil

For larger coils, similar increment in resistivity, but ramping times decreases from 25 hours → 2 hours.
→ SS insulation becomes necessary!

Application I: Stacked Small ID Coils in NMR
Similar to the SS Insulated Test Coil, 295 mH

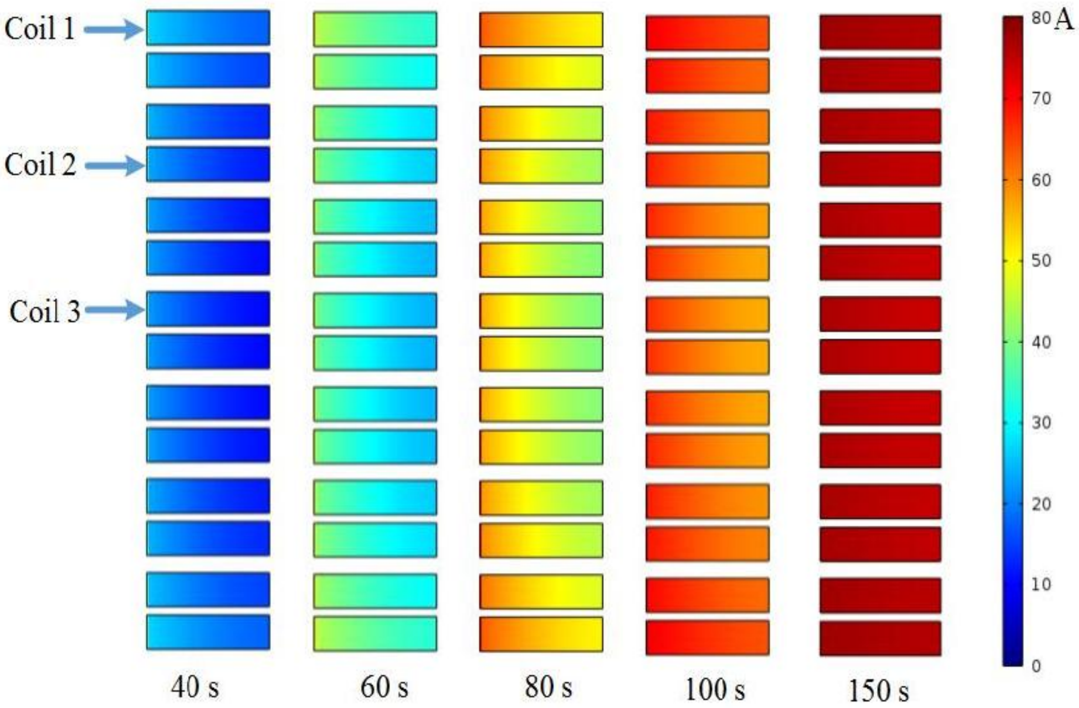


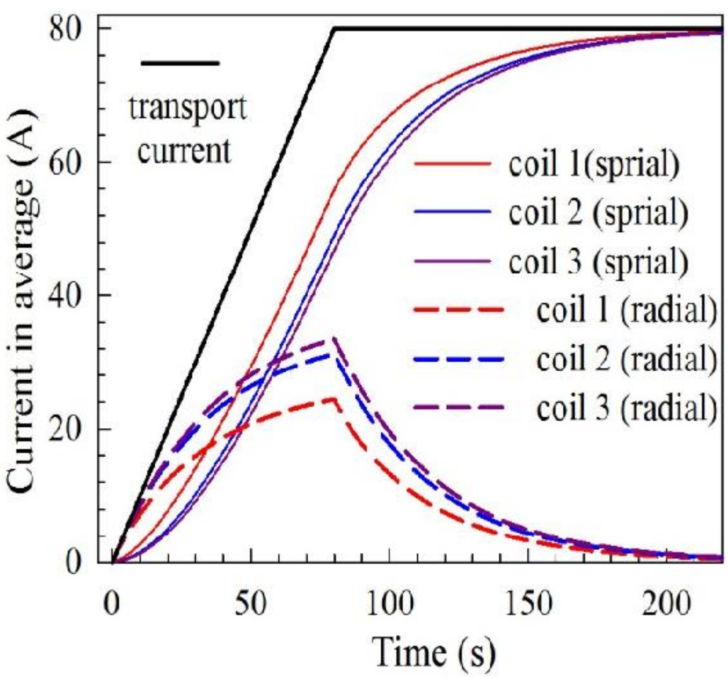
Minimum ramping time versus # of DP coils.



*V*peak VS #of the DP coils.

NMR Applications: Stacked Small ID Coils



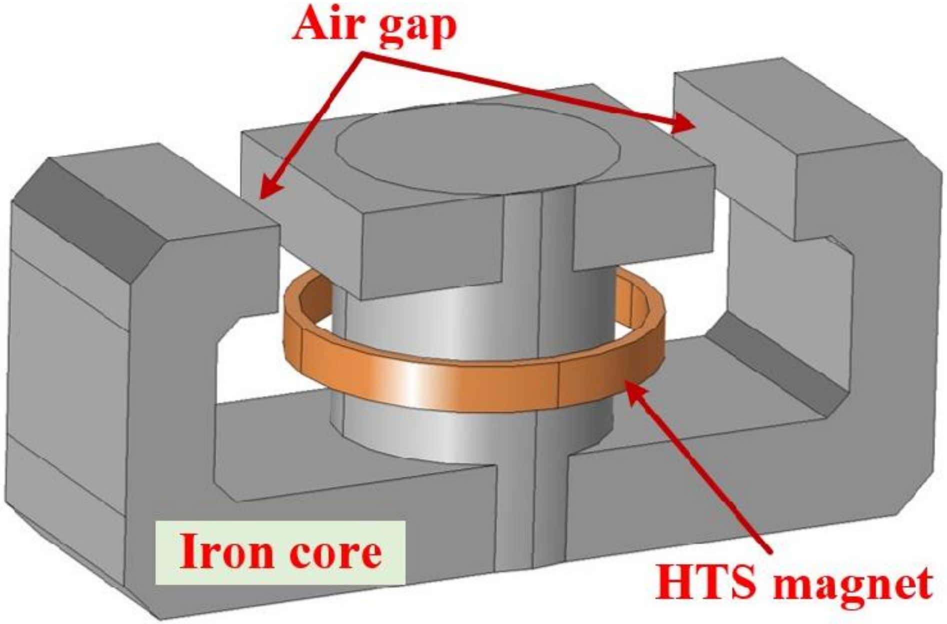


1) Ramping rate=1 A/s, magnet with 7 DP coils,
2) Time resolved distribution of tangential-component current,
3) Difference exits between top and middle coils

1) Total transport current (power supply)
2) Tangential current in coils 1 – 3
3) Radial current in coils 1 -3

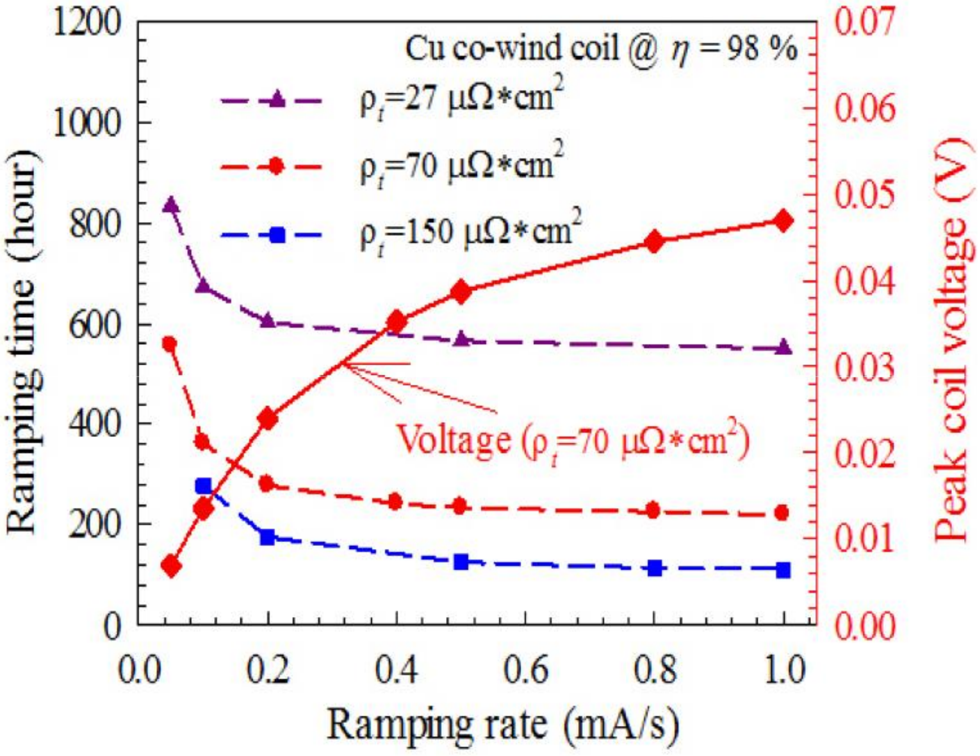
Application II – HTS DC Induction Heater

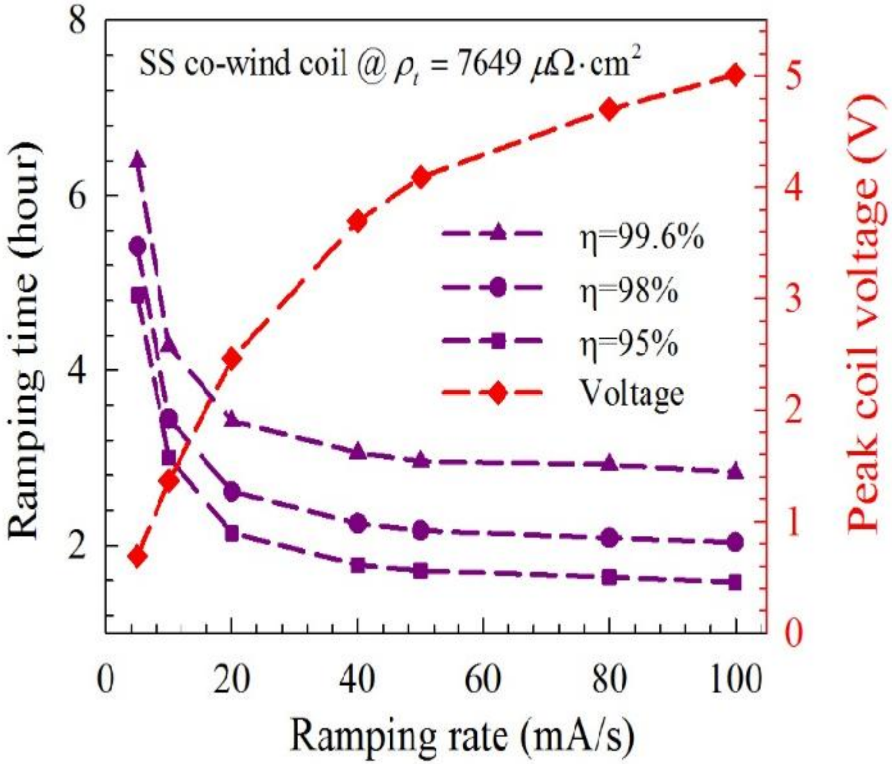
- Magnet:
  - DP coil: ID = 2 m, 130*2 turns
  - Magnet: 10 DP coils
  - Operation: I_{op}=80A, B =0.4 T (air gap)
  - Self-inductance: 31 H (without iron), 132 H (with iron)
  - Preliminary design only for this analysis use (single conductor winding)



IEEE TRANS ON ASC, VOL. 25, NO. 3,JUNE 2015, 4600305

Application B – HTS DC Induction Heater Cu VS SS Co-winding



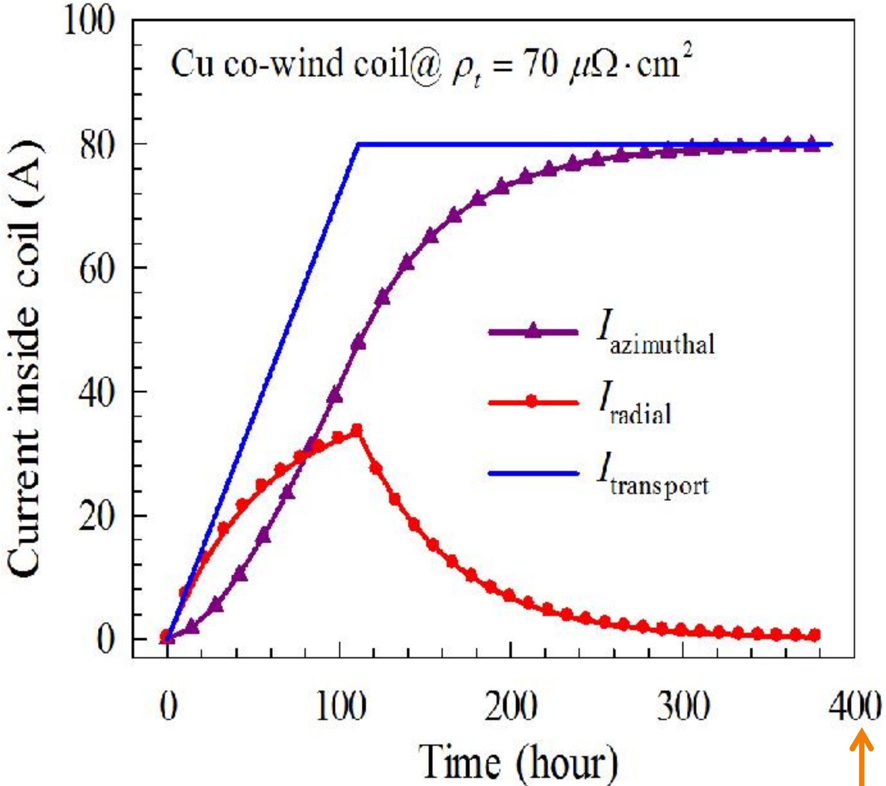


If the coils is wound with Cu strips
Rampig time will be up to 200 hours

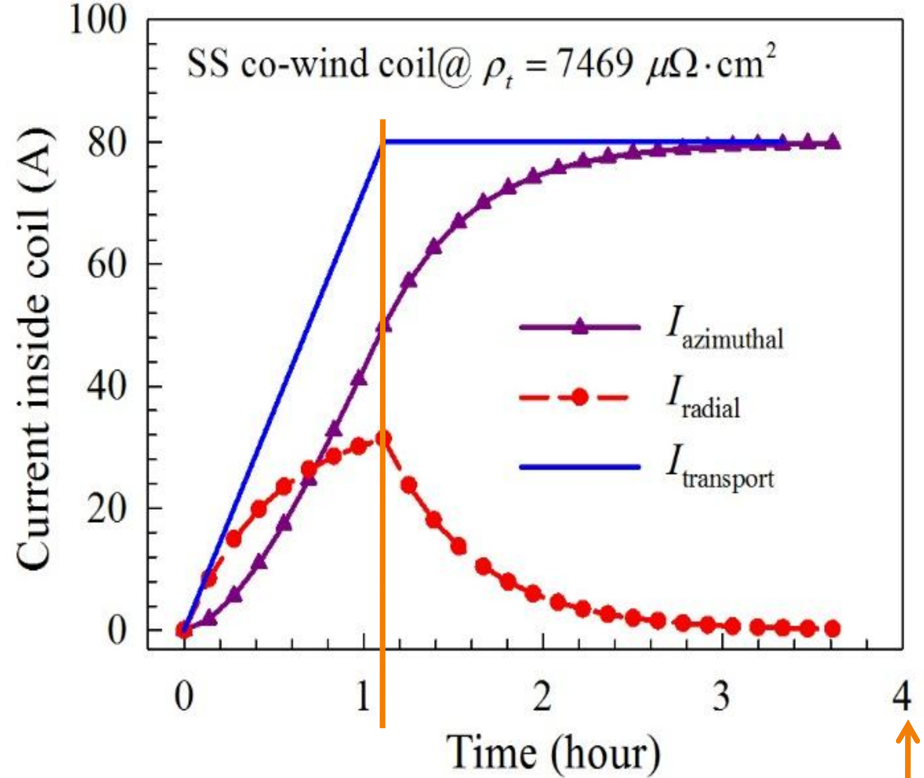
If the coils is wound with SS strips
Rampig time will be below 2 hours

Current Flow Comparison Between (Cu VS SS)

Ramp rate 0.2 mA/S



Ramp rate 0.02 A/S

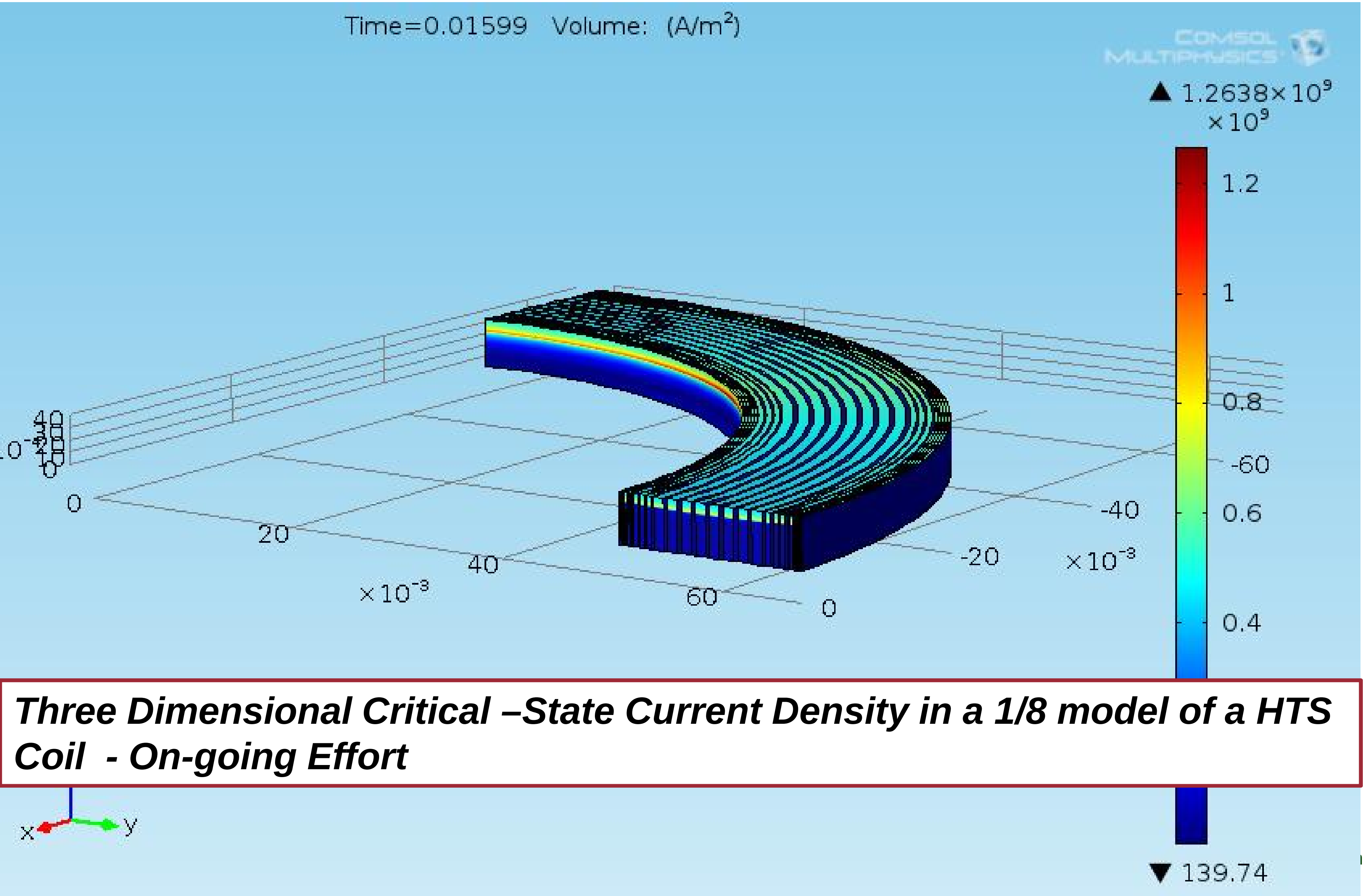


Although in the same pattern, but 100 times shorter in ramping time!

Conclusions

- Metallic insulation is an effective approach for HTS coil protection during quench and other unpredicted accidents
- Although metallic insulation becomes disadvantage during charge ramping
  - Cu insulation is still ok for small diameter coil application (like NMR)
  - But for large-scale applications, Cu insulation results in much more time (up to 100 hours) in ramping,
    - » Thus, SS insulation becomes necessary
- More studies further needed
  - Thermal behaviors due to radial current component → increased temperature during charge ramping
  - Thermal management during fast-discharge needs more complete modeling, other than MITTs function prediction
  - Conductors cabling to reduce the magnet inductance
- HTS magnet technology needs more R&D as it positively progresses towards broader applications – particularly high energy physics.

Thank-You



Three Dimensional Critical –State Current Density in a 1/8 model of a HTS Coil - On-going Effort

Appendix
Definition of Minimum Ramping Time