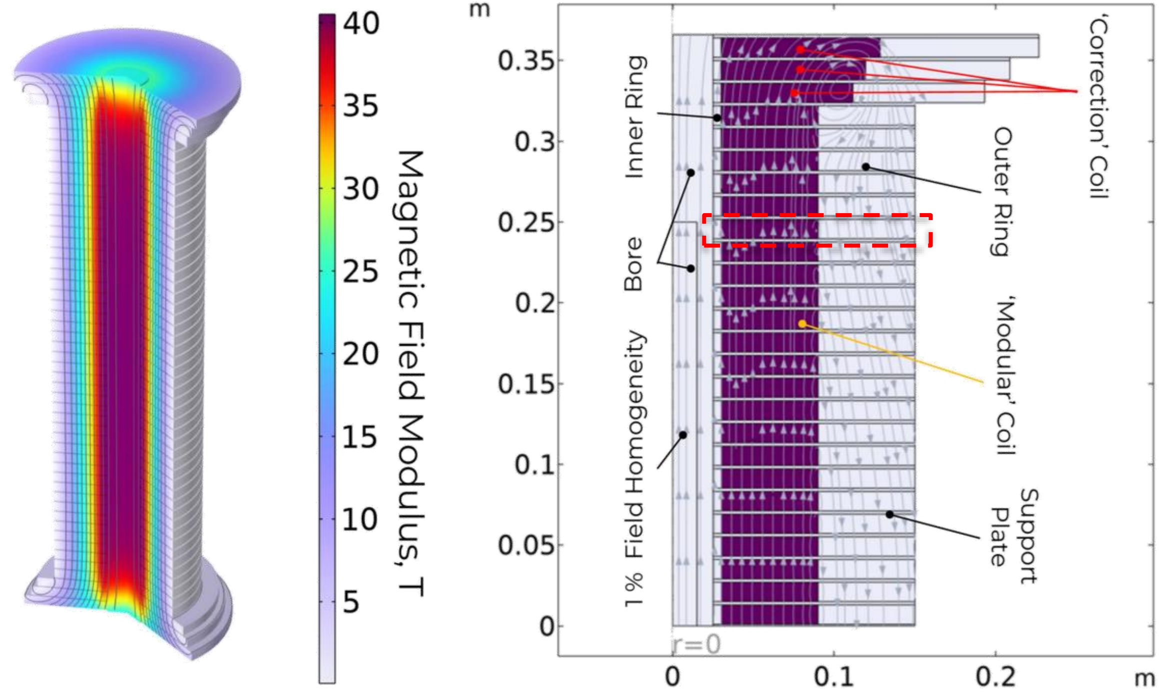
Experimental tests for winding technology of Final Cooling Solenoid

M. Abdel Hafiz
On behalf of Final Cooling Solenoid working group

Final Cooling Solenoid



B. Bordini & al., 2024

- 40 T , 50 mm bore diameter
- Each pancake is in a solder matrix to redistribute stress

Proposal for widing a pancake :
How does that effect the tape properties ?

Final Cooling Solenoid
Outline

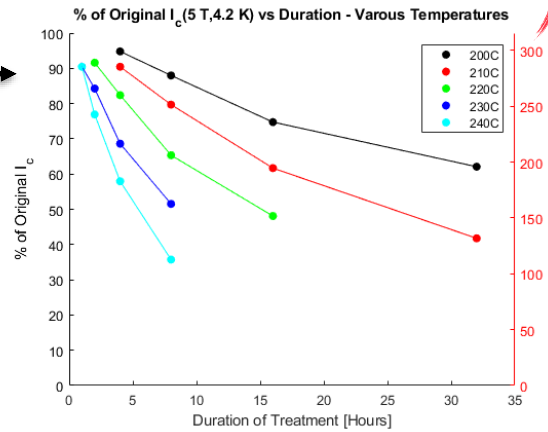
- Effect of Temperature on tape
- Description of the winding
- Effect of the winding proposal on pancake properties
- Chemical etching to control transverse resistance
- Effect of the etching on pancake properties

All results presented *from this study* have been performed on a Theva TPL4421

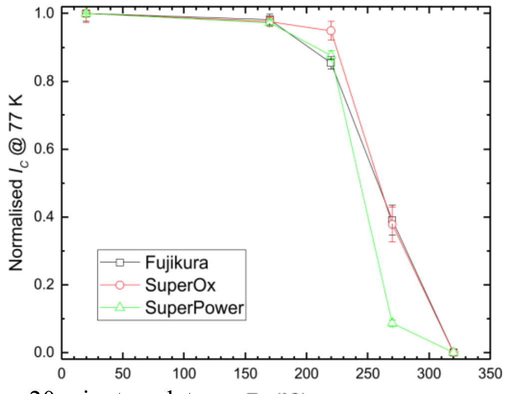
Temperature influence on I_C

Literature

- I_C degrades with time and temperature
- 2 mechanisms of degradation :
  1. Oxygen-out diffusion from grain boundaries of ReBCO layer
  2. T > 250°C → Oxygen-out diffusion from grains of ReBCO layer
- Heat treatment cycle does not affect
- Stabilizer thickness is a parameter of degradation
- Depends on the manufacturing process
- Vacuum could have an effect

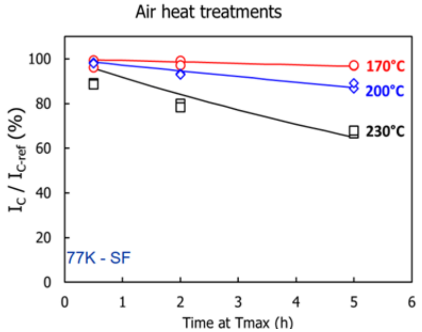


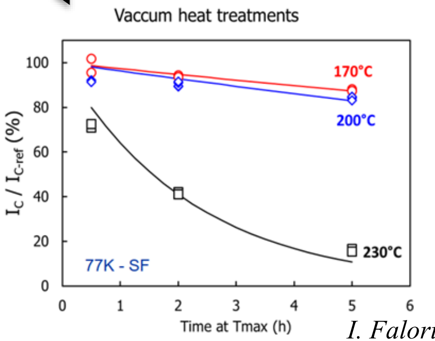
G. Bradford & al. MT26 (2019)



20 minutes plateau T_{HT} (°C)

M. Bonura & al. (2022)



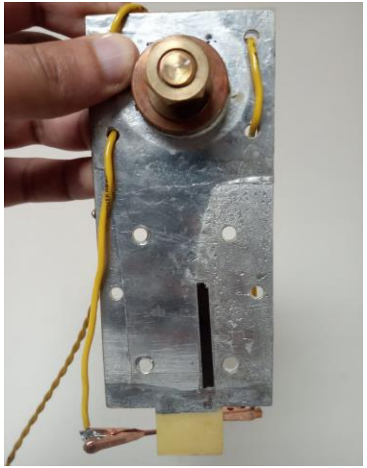


I. Falorio (2020)

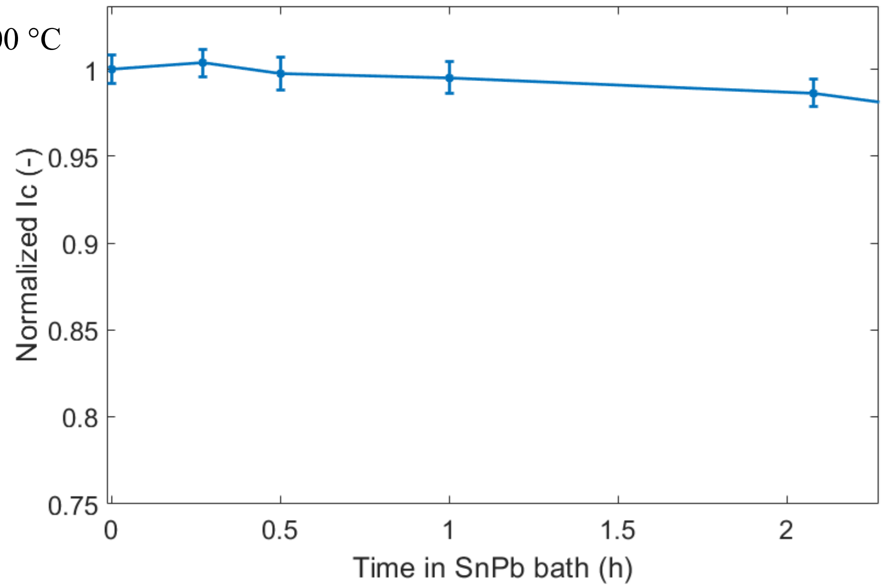
Temperature influence on I_C
Preparing samples

Sample holder :
- G10 insulating plate (~ 1 mm)
- Both sides :
  - Cu coating (~75 µm)
  - SnPb coating

Sample cycled :
- Coating tape and soldered to the sample holder
- I_C measurement @ 77K
- Heated in solder bath @200 °C
- Cycling process



Sample Holder



- **Preparing and coating samples do not visibly affect I_C on measured length**
- **I_C Degradation of Theva TPL tape < 3% after 2h @200°C in SnPb bath**

Hot winding

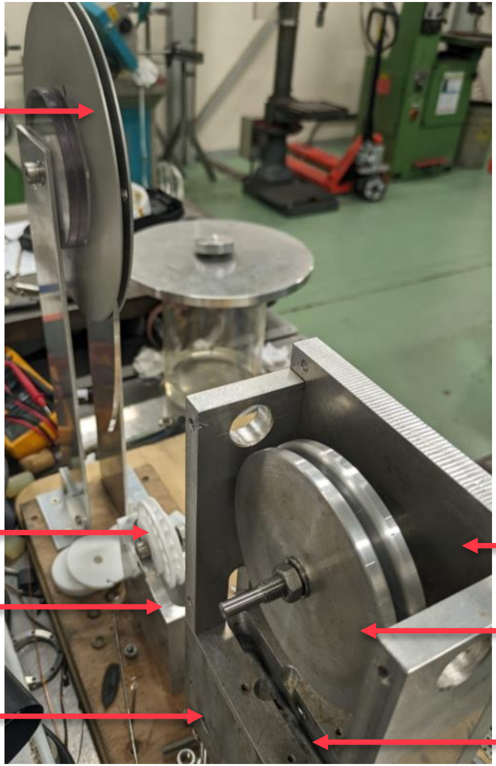
Winding tool prototype

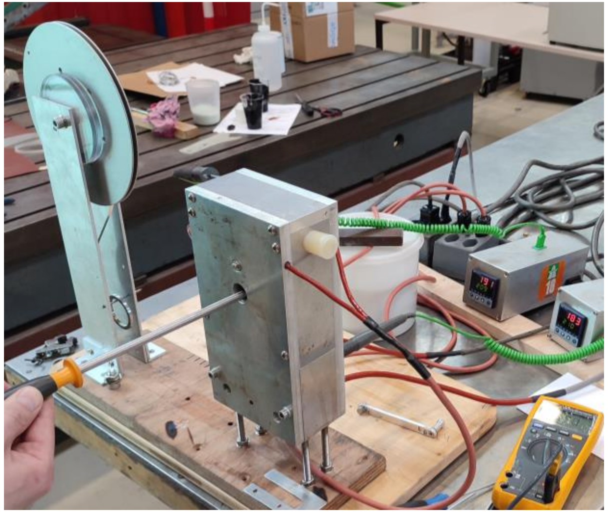
Tape spool

Rotating wheel

Flux bath

Heater slot





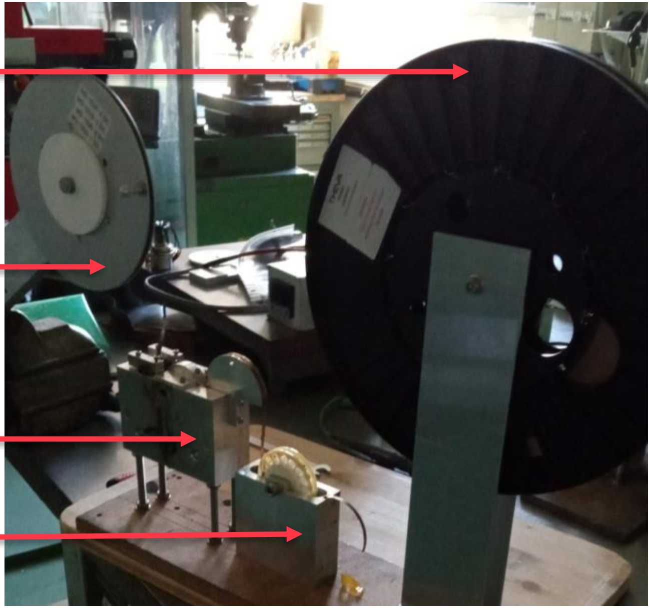
(Opened) Oven

Wound spool

Solder bath

Hot winding
Winding protocol

1. **Precoating tape**
   - Heat up to 200°C to melt SnPb (~15 min)
   - Tape passes through flux and solder (~ 10 s)
   - Gravity seems to be enough to remove ***some*** excess of solder
   - Precoating tapes allows to :
     - Control coating of tapes
     - Remove flux bath during winding process



Hot winding
Winding protocol

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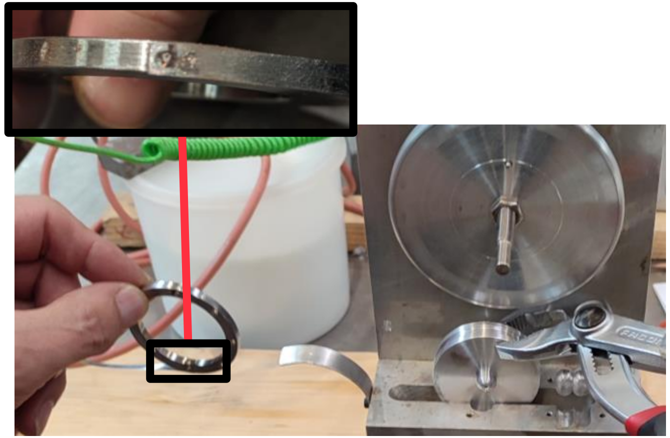
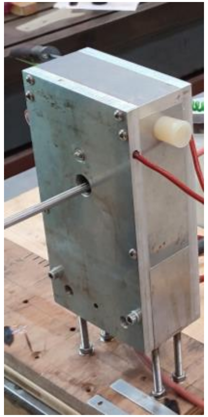
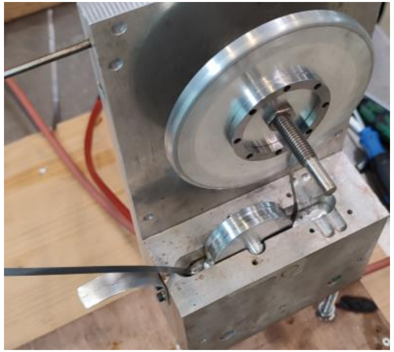
   - Precoating tapes allows :
     - Control coating of tapes
     - Remove flux bath during winding process
2. **Starting winding**
   - Heat up the oven to 200°C to melt SnPb (~45 min)
   - Remove the door & install the mandrel
     - Invar mandrel has been chosen for these tests
       - Invar shrinkage from 473K to 77K is lower than HTS and limiting radial tensile stresses in the pancake during cooling down
       - Invar bounds well and easily to SnPb
     - Tape is pre-installed on the mandrel
       - Hooked in a groove
       - Spot welded to the mandrel
   - Close the door and reheat to 200°C (~20 min)







Hot winding
Winding protocol

1. **Precoating tape**
   - Heat up to 200°C to melt SnPb (~20 min)
   - Tape passes through flux and solder (~ 10 s)
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   - Precoating tapes allows to :
     - Control coating of tapes
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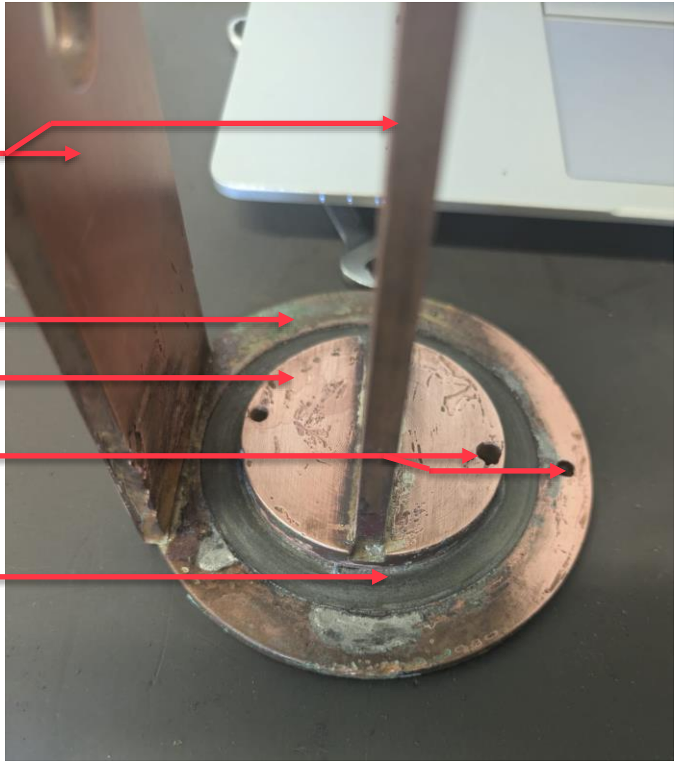
2. **Starting winding**
   - Heat up the oven to 200°C to melt SnPb (~45 min)
   - Remove the door & install the mandrel
     - Invar mandrel has been chosen for these tests
       - Invar shrinkage from 473K to 77K is lower than HTS and limiting radial tensile stresses in the pancake during cooling down
       - Invar bounds well and easily to SnPb
     - Tape is pre-installed on the mandrel
       - Hooked in a groove
       - Spot welded to the mandrel
   - Close the door and reheat to 200°C (~20 min)
3. **Winding pancake**
   - No controlled tension is applied nor measured
   - Winding duration for 15m of tape took 20 to 40 minutes
4. **Cooling down**
   - To room temperature (~ 1h)

2h of heating for the tape
4 Pancakes successfully prepared

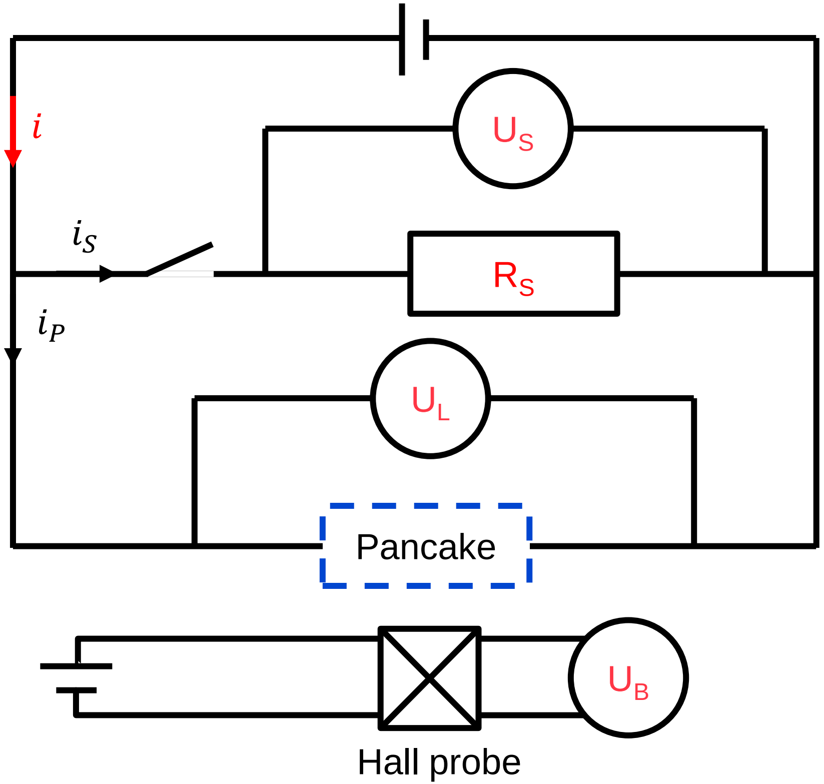
Pancake Properties

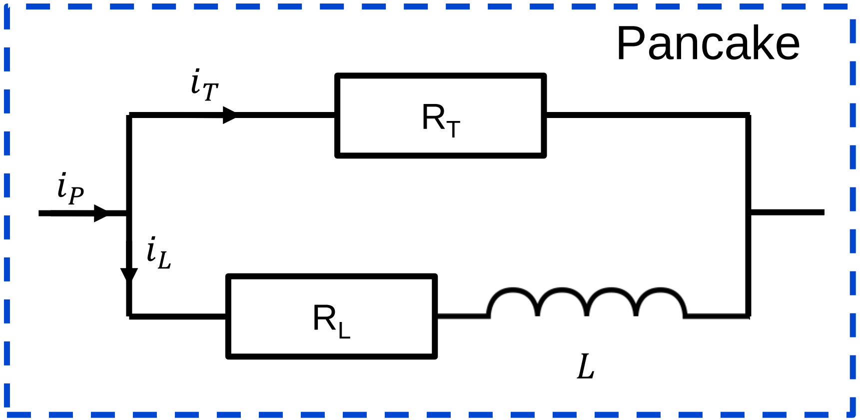
Preparation for experiment

1. **Installing current leads**
    - Ensure electrical contact from rings to pancake without melting the pancake (183°C)
        - Low temperature solder ($Bi_{58}Sn_{42}$ 138°C)
2. **Tests performed @77K**
    - Measure critical current I_C of the pancake
        - Steady state study with low ramp rate
    - Measure time constant τ
        - Steps current
    - Hall Probe located in the center of the pancake to measure central field



Pancake Properties
Experiment Scheme

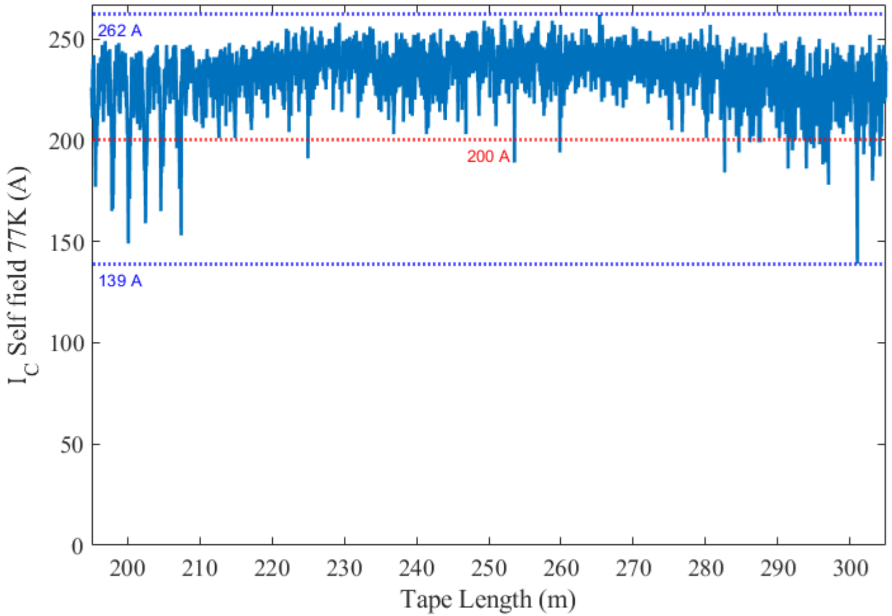




i	Power supply current
i_S	Shunt current
i_P	Pancake current
i_T	Transverse *(radial)* current
i_L	Lenghtwise *(azimuthal)* current
U_S	Shunt voltage
U_L	Pancake voltage
U_B	Hall Probe Voltage

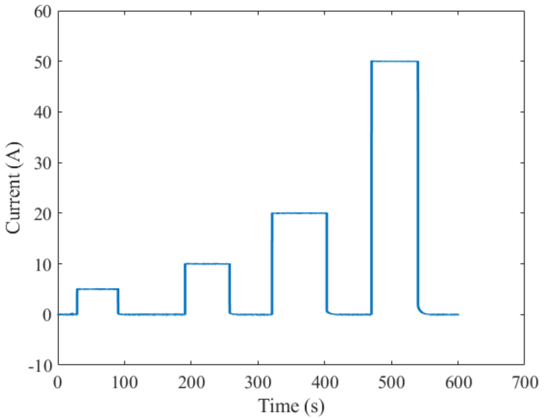
Pancake Properties

Tape I_C map

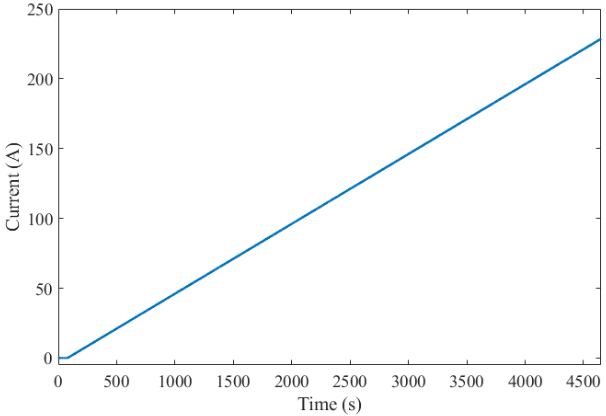


	Pancake 1	Pancake 2	Pancake 3	Pancake 4
Inner radius	24 mm	24 mm	30 mm	30 mm
Outer radius	30.2 mm	31.6 mm	35.6 mm	35.6 mm
Nb of turns	74	84	64	64
Mean thickness per tape	84 µm	90 µm	88 µm	88 µm
Inductance	479 µH	606 µH	474 µH	474 µH

Pancake Properties



Transient study: Steps at different current



Steady state study : ramp of 0.05A/s

	Pancake 1	Pancake 2	Pancake 3	Pancake 4
Inner radius	24 mm	24 mm	30 mm	30 mm
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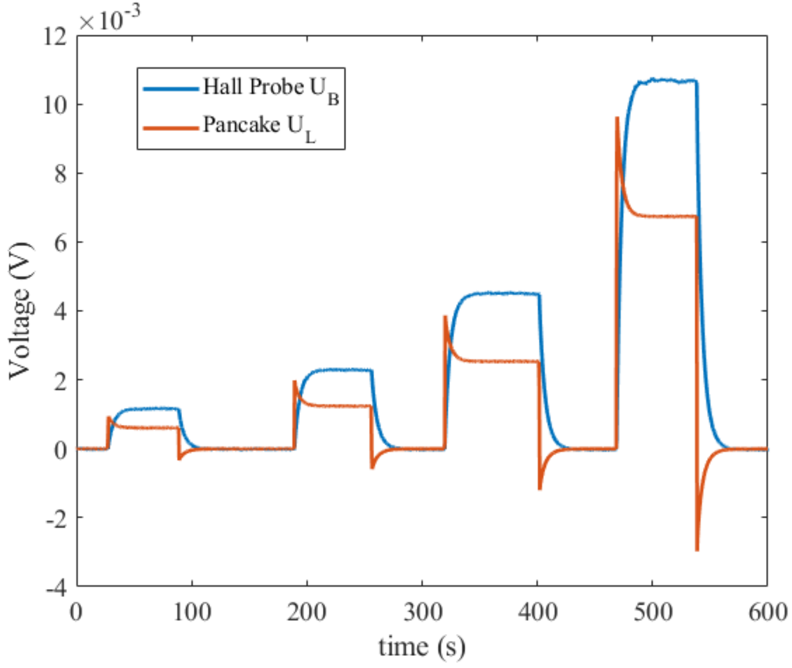
Pancake Properties
Transient Study



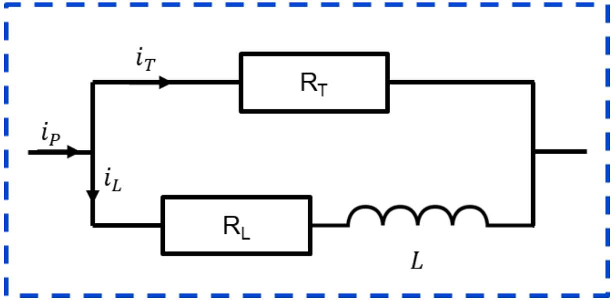
$\tau\ (s)$	Charge	Discharge
5 A	4.87	4.92
10 A	4.70	5.05
20 A	4.78	5.02
50 A	4.60	4.83

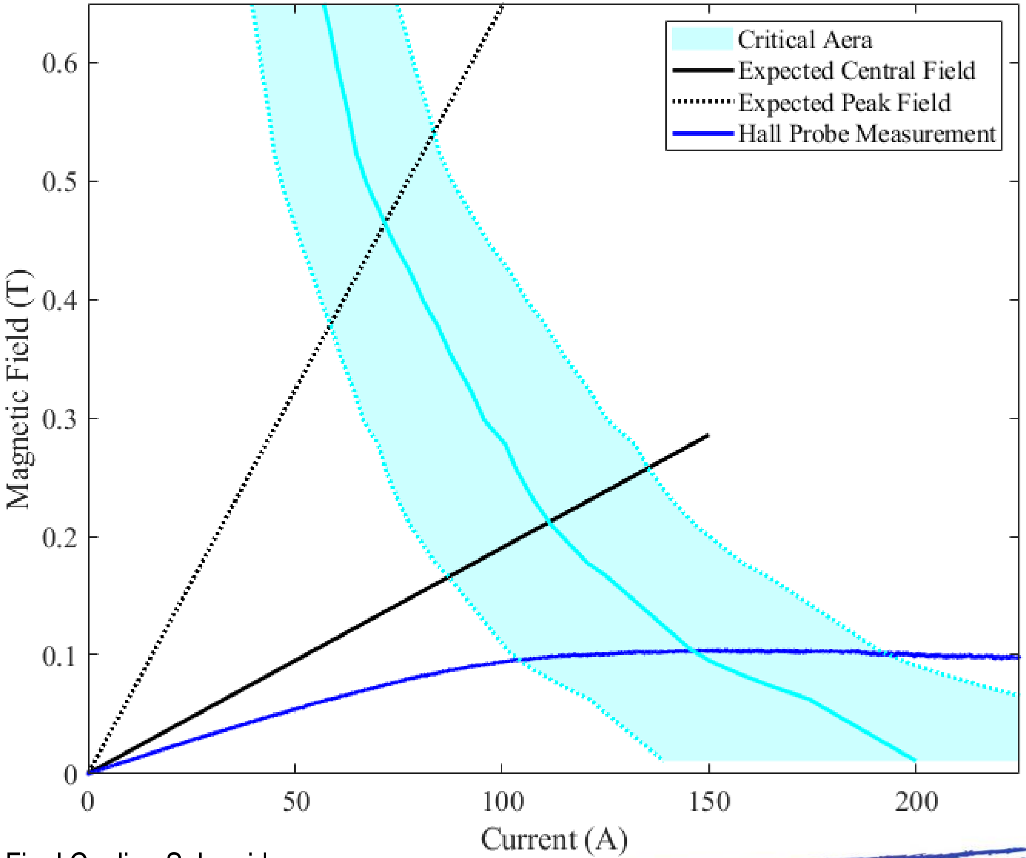
$$\tau = \frac{L}{R_{eq}} \text{ with } R_{eq} = \int \frac{\rho_{eq}}{2\pi r w} dr$$

	$\tau\ (s)$	$\rho_{eq}\ (\mathrm{m\Omega.mm})$
Pancake 1	5.2	10.1
Pancake 2	4.8	11.5
Pancake 3	1.6	43.5
Pancake 4	3.1	22.5

Pancake Properties
Steady State Study

Pancake

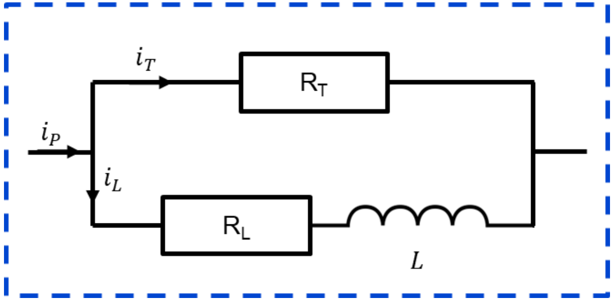




Pancake Properties

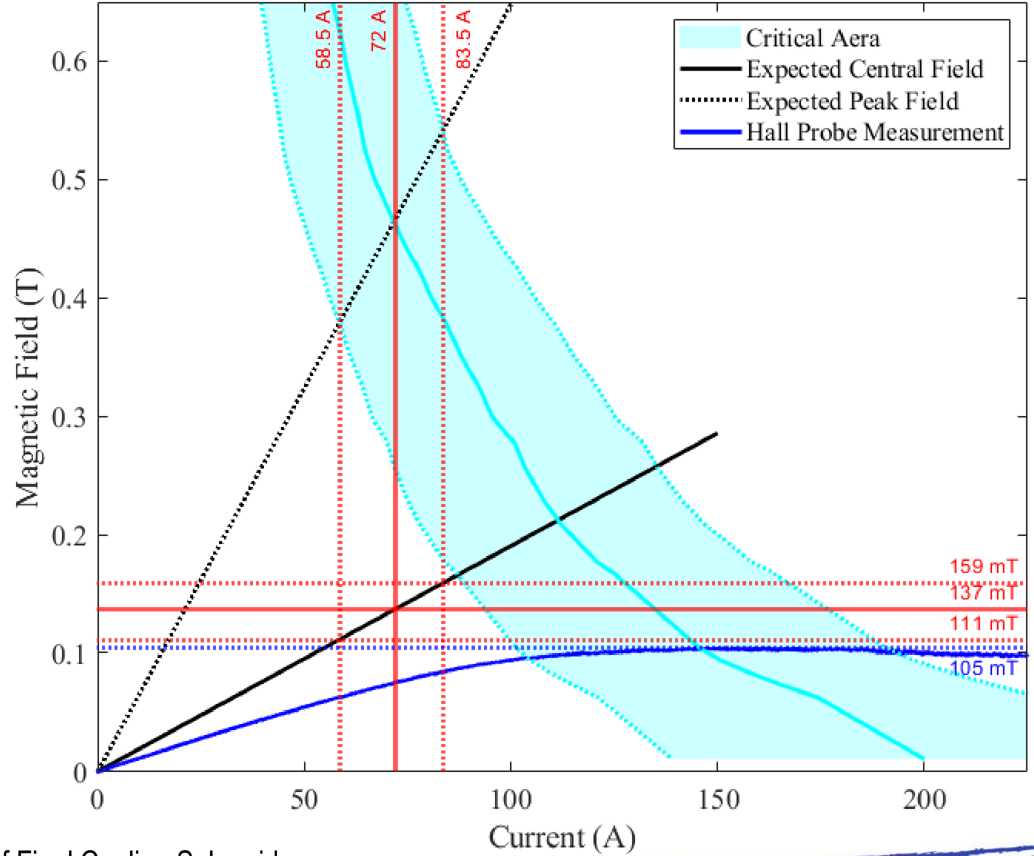
Steady State Study

Pancake



'Maximum' Field (mT)	Expected	Measured
Pancake 1	129	115 **(89%)**
Pancake 2	137	105 **(77%)**
Pancake 3	93	72 **(77%)**
Pancake 4	93	68 **(73%)**

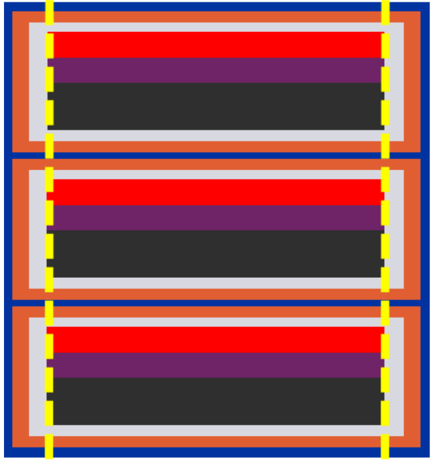
75 % of the expected maximum field



Chemical Etching

MuCol

International UON Collider Collaboration



Scheme of tapes stack cross section

Layer properties for Theva TPL4421 4 mm width *(tape property sheet)*

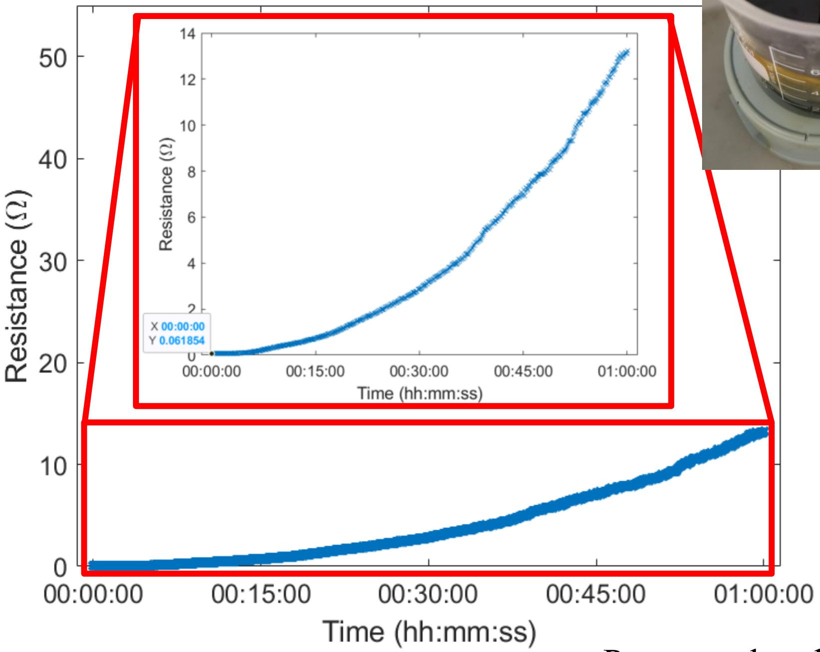
- ~ 10 µm Cu stabilizer
- ~ 1 µm Ag
- ~ 4.5 µm HTS layer
- ~ 3.5 µm buffer layers *(insulating MgO)*
- ~ 48 µm C-276 substrate
- ~ 15 µm Sn-Pb solder *(estimation)*

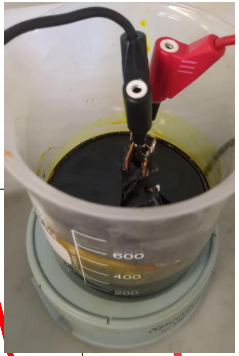
Ohmmeter

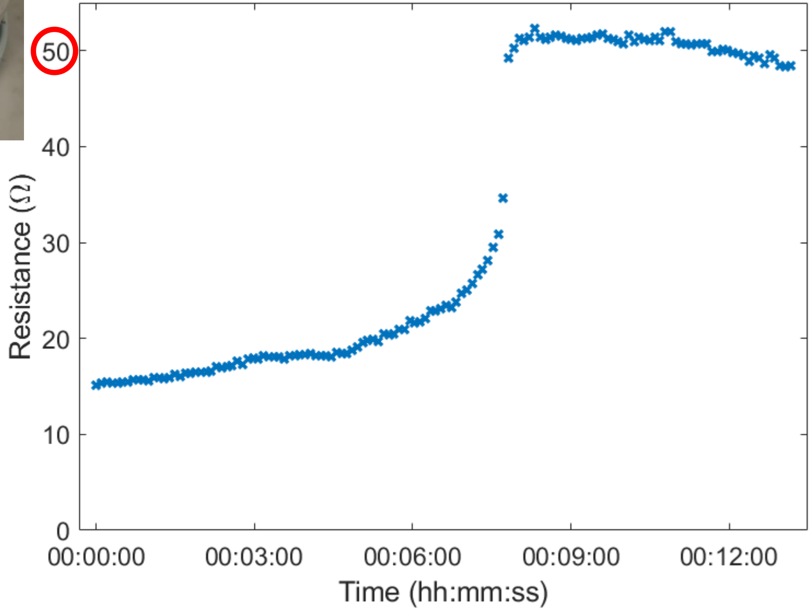
Magnetic stirrer

Chemically *($FeCl_3$ etching)* remove both side of the tape to increase resistance

Chemical Etching





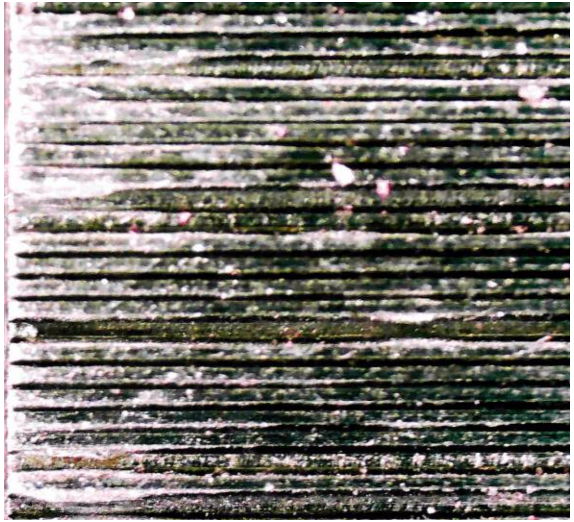


Program shut down for a few minutes

Chemical Etching

< 0.05 Ω

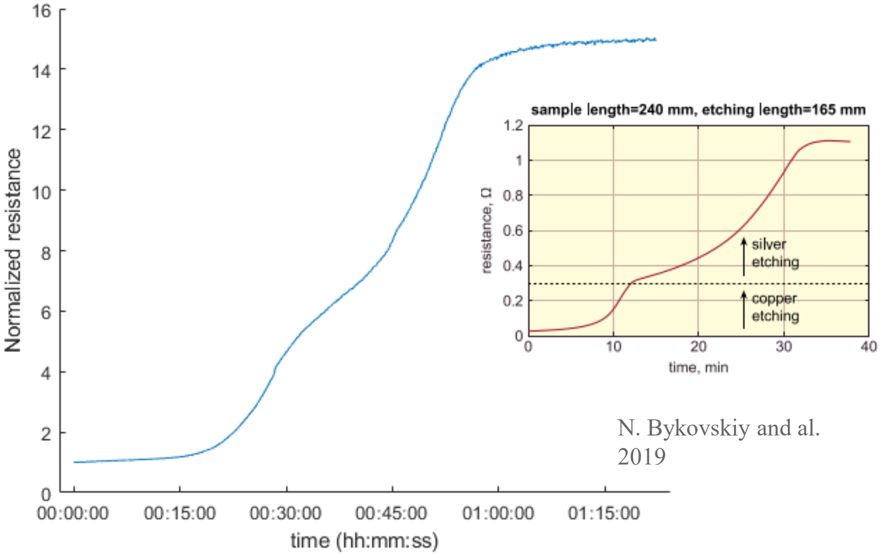
0.5 Ω



200 Ω

Resistance @77K increased by 4 order of magnitude after etching
What about I_C ?

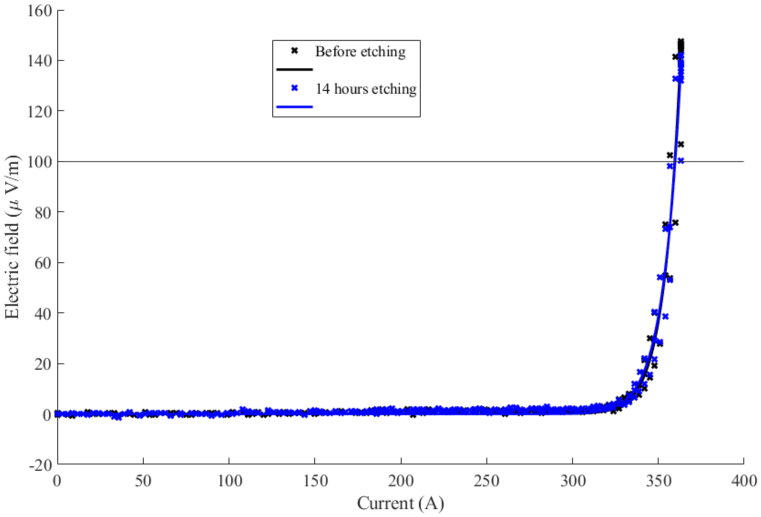
Chemical Etching



N. Bykovskiy and al. 2019

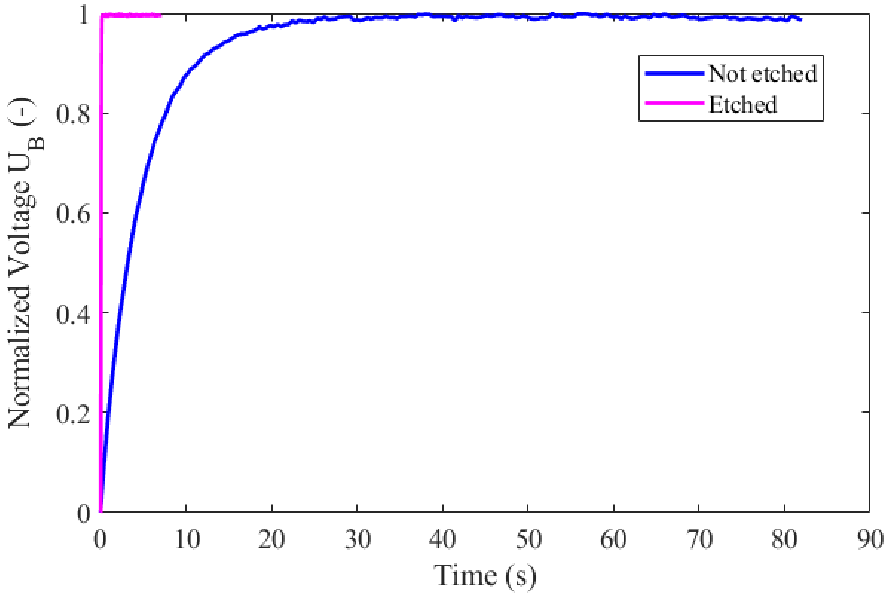
- Cu removed in ~30min
- Ag removed (?) in ~ 1h

Two tapes soldered to each other



Etching seems to have no effect on I_C need to be determined
Further experiments required to confirm

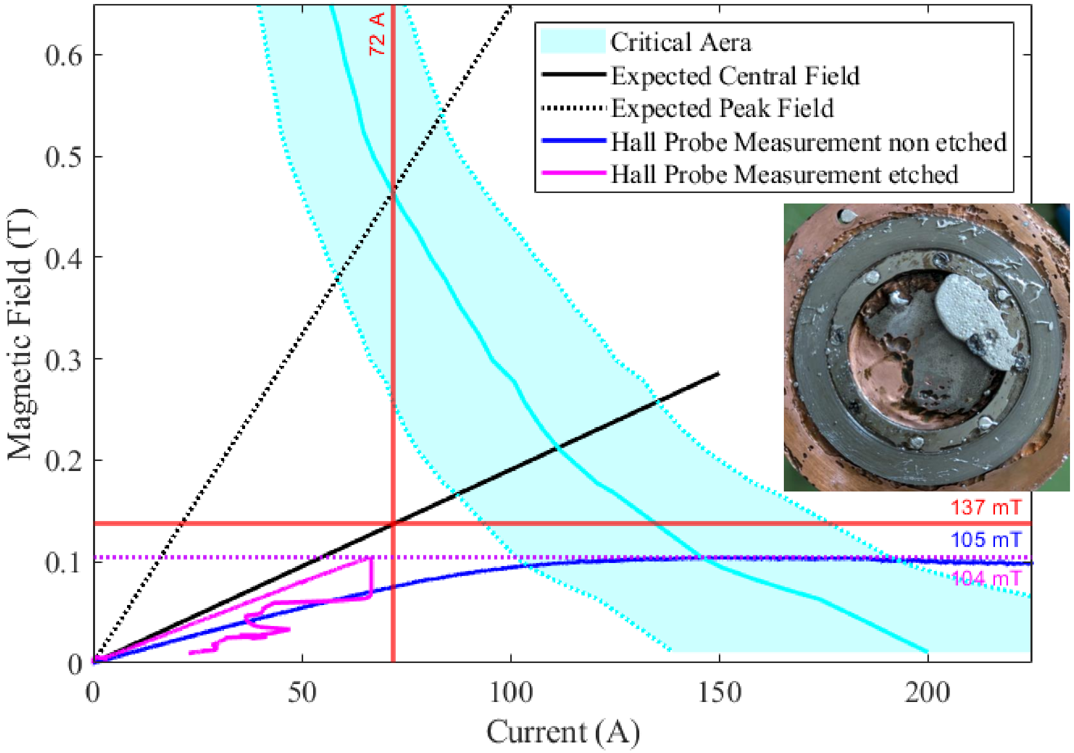
Chemical Etching
Pancake Properties



		τ (s)	ρ_{eq} (mΩ.mm)
Pancake 1	raw	5.2	10.1
	etched	0.4	268
Pancake 2	raw	4.8	11.5
	etched	< 0.04	> 1384
Pancake 3	raw	1.6	43.5
	etched	< 0.02	> 3480
Pancake 4	raw	3.1	22.5
	etched	< 0.02	> 3480

Time constant decreased by a factor 100

Chemical Etching
Pancake Properties



'Maximum' Field (mT)	Measured	
Pancake 1 129	Non etched Etched	115 **(89%)** 98 **(76%)**
Pancake 2 137	Non etched Etched	105 **(77%)** 104 **(76%)**
Pancake 3 93	Non etched Etched	72 **(77%)** 50 **(54%)**
Pancake 4 93	Non etched Etched	68 **(73%)** 52 **(56%)**

- 15 % of from the non-etched maximum field

Conclusion

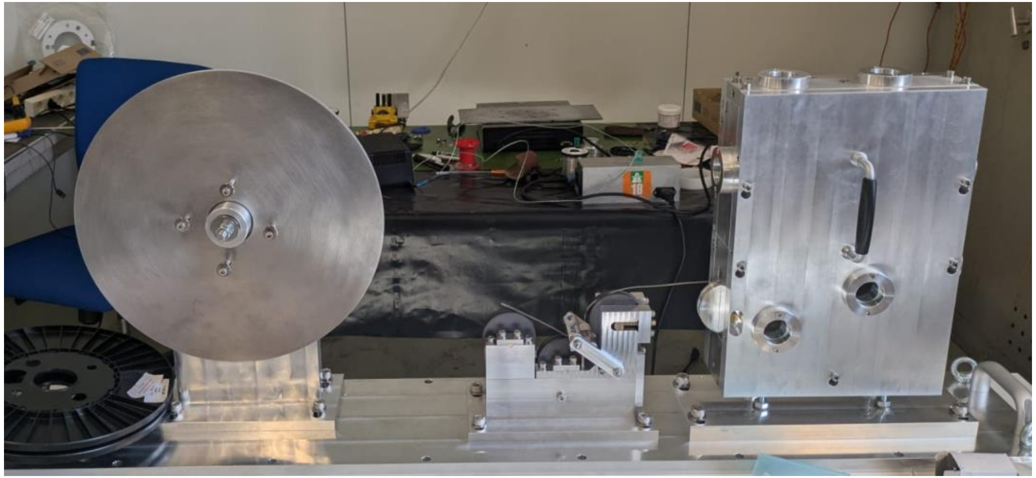
These conclusions can only be assessed for Theva TPL 4421 tapes :

- I_C of the tape degrades by less than 5% after 2h in solder bath
- We have no control of current distribution in the pancake
  - It is difficult to define a critical current for the pancake
  - The magnetic field produced is about 25% lower than expected
- Chemical etching increases the transverse resistance by about 4 order of magnitude and does not seem to affect I_C
  - Concerning the pancakes it reduces the time constant by at least a factor 100
  - The magnetic field is reduced by another 15%
    - It is not clear whether that is the effect of etching, or the presence of defects already here highlighted by the removal of the stabilizer
  - *Thermo-mechanical tests are needed to characterize the properties of an etched stack*

Conclusion

On going work :

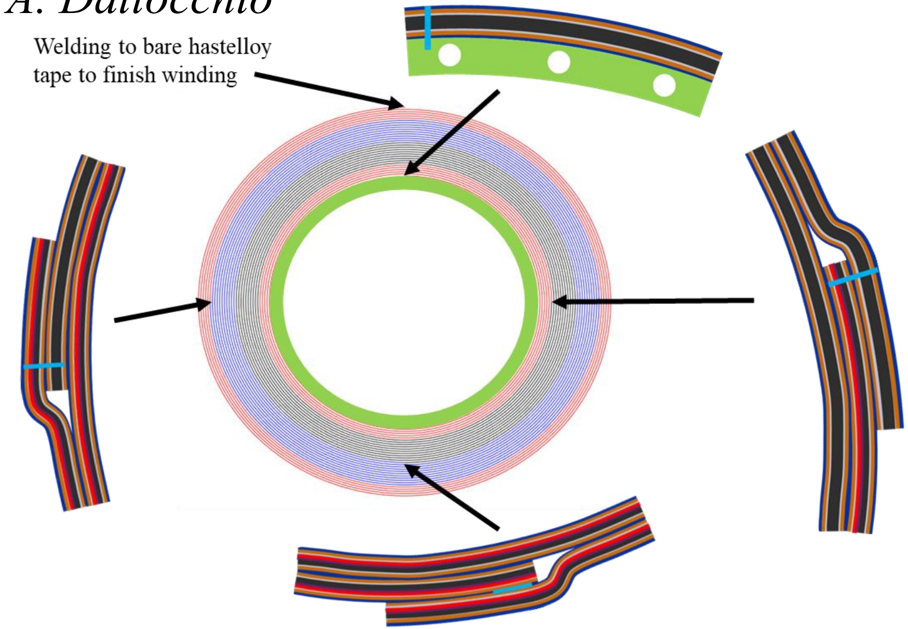
- New winding tool has been machined and assembled for further pancake production *(F. Sanda, A. Kolehmainen, A. Dudarev, A. Dallocchio)*



Conclusion

On going work :

- New winding tool has been machined and assembled for further pancake production *(F. Sanda, A. Kolehmainen, A. Dudarev, A. Dallocchio*
- Problematic of the joints
  - Tape to inner/outer ring
  - Tape to outer ring
    - ➢ Layer jump



- Mandrel
- Copper/Hastelloy tape (inner)
- HTS tape inwards
- HTS tape outwards
- Copper/Hastelloy tape (outer)

Thank you for your attention

M. Abdel Hafiz
On behalf of Final Cooling Solenoid working group

Temperature influence on I_C
Preparing samples

Sample cycled :

- Preparing sample
- I_C measurement @ 77K
- Heated in solder bath @200 °C
- Cycling process

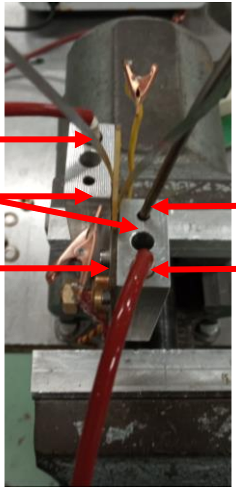
Sample holder :

- G10 insulating plate (~ 1 mm)
- Both sides :
  - Cu coating (~75 µm)
  - SnPb coating
  - Extremity etched for clamping voltage tapes

Sample preparation :

1. Screw Al blocs to sample holders
2. Heat up to 200°C to melt SnPb (~10 min)
3. Insert tape within groove (~ 1 min)
4. Wait for cooling down (~10 min)

Sample Holder



Sample Preparation

Bloc and heaters @200°C for 25 minutes for test

1. Preparing sample does not degrade I_C of measured length
2. Coating sample does not visibly affect I_C

@77K

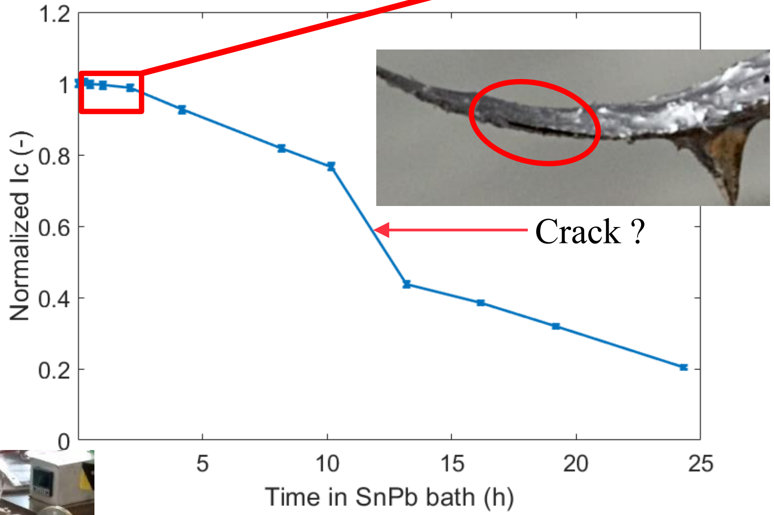
Temperature influence on I_C

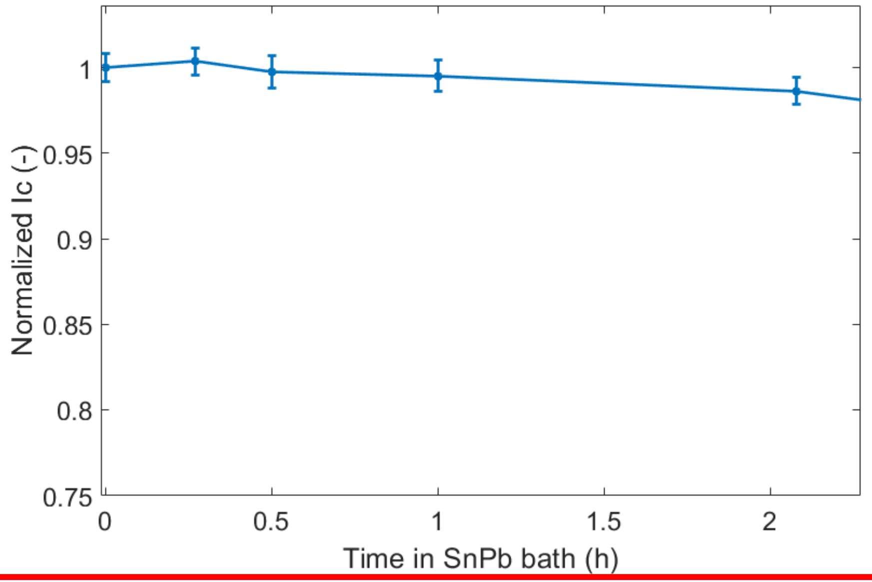
Experiment

Sample cycled :

- Preparing sample
- I_C measurement @ 77K
- Heated in solder bath @200 °C
- Cycling process

$I_0 = 190$

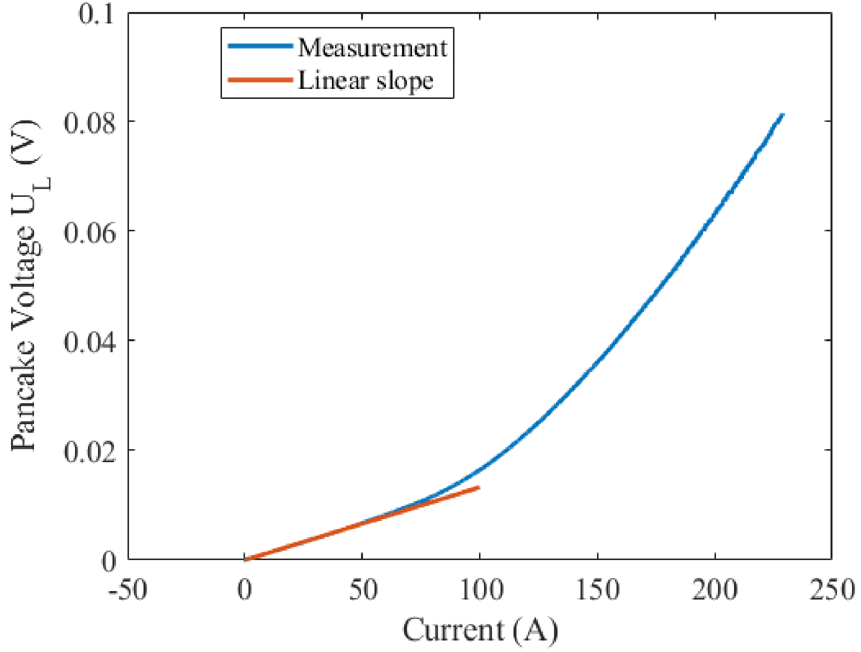


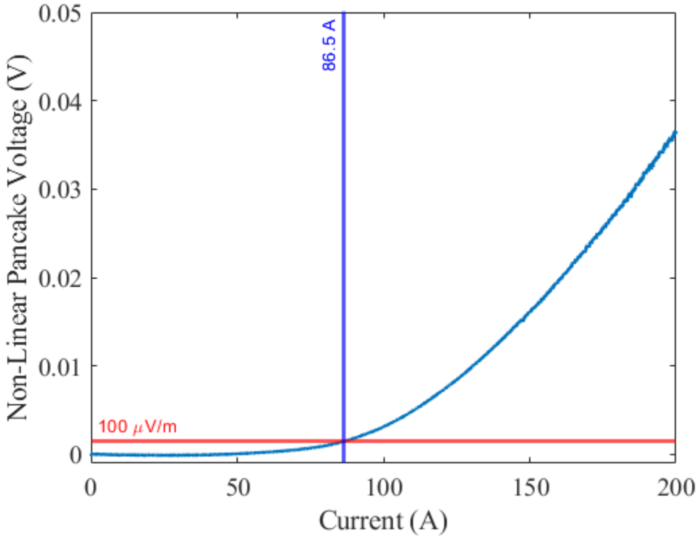


Solder bath

Degadation of Theva TPL tape < 2% after 2h @200°C in SnPb bath

Pancake Properties



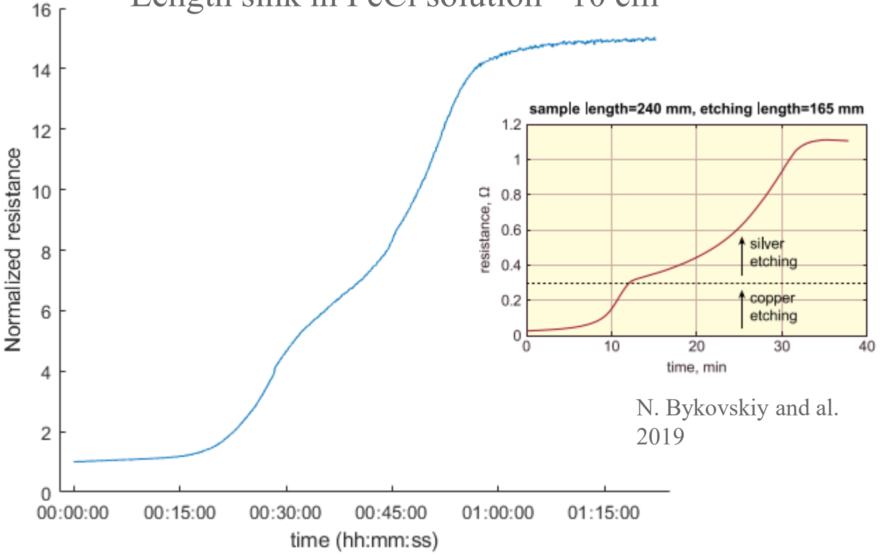


Critical Current (A)	Expected	Measured
Pancake 1	75	54
Pancake 2	72	86
Pancake 3	76	53
Pancake 4	76	143

Single tape

How much time needed to remove copper from side ?

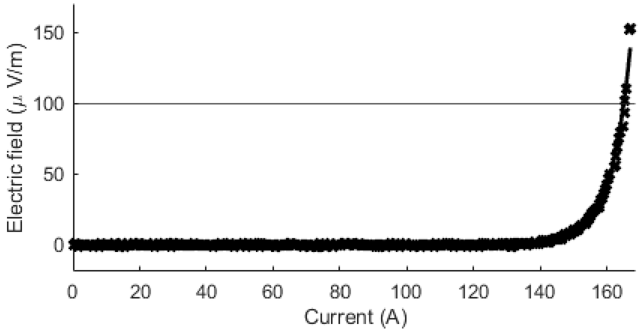
- Lengthwise resistance measured in FeCl @ room temperature
- Length sink in FeCl solution ~10 cm



N. Bykovskiy and al. 2019

- Cu removed in ~30min
- Ag removed (?) in ~ 1h

- I_C measured @77K at the end of R measurements (~ 1h20)

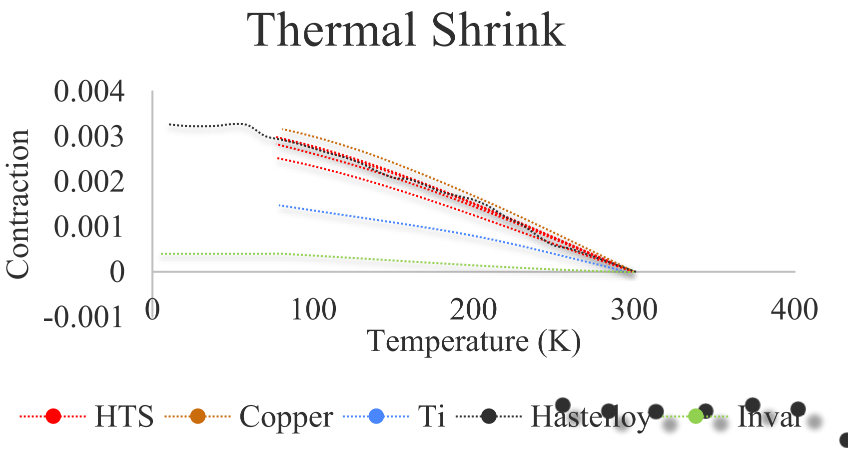


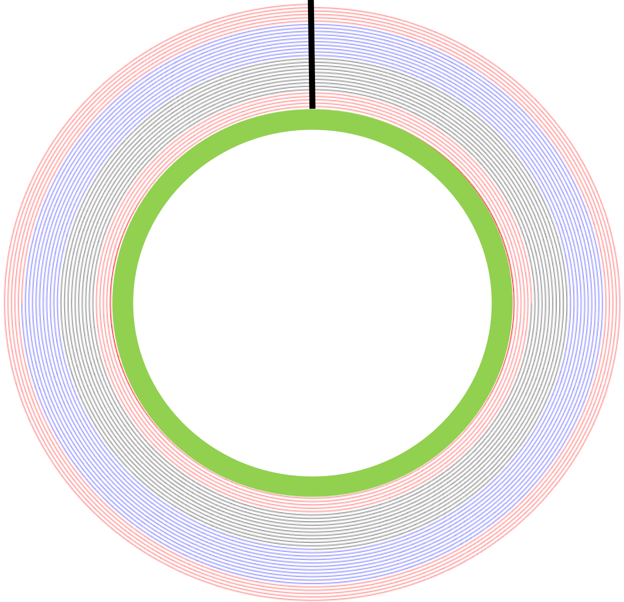
- Degradation < 20%

Single tape still superconductive after removing Cu and Ag(?) (1h20) in FeCl
Further experiments required to confirm
According to N. Bykovskiy, depends on the tape

Mandrel

- Mandrel thermal shrinkage be lower than tape
  - *Only lengthwise (tape) thermal shrinkage found*



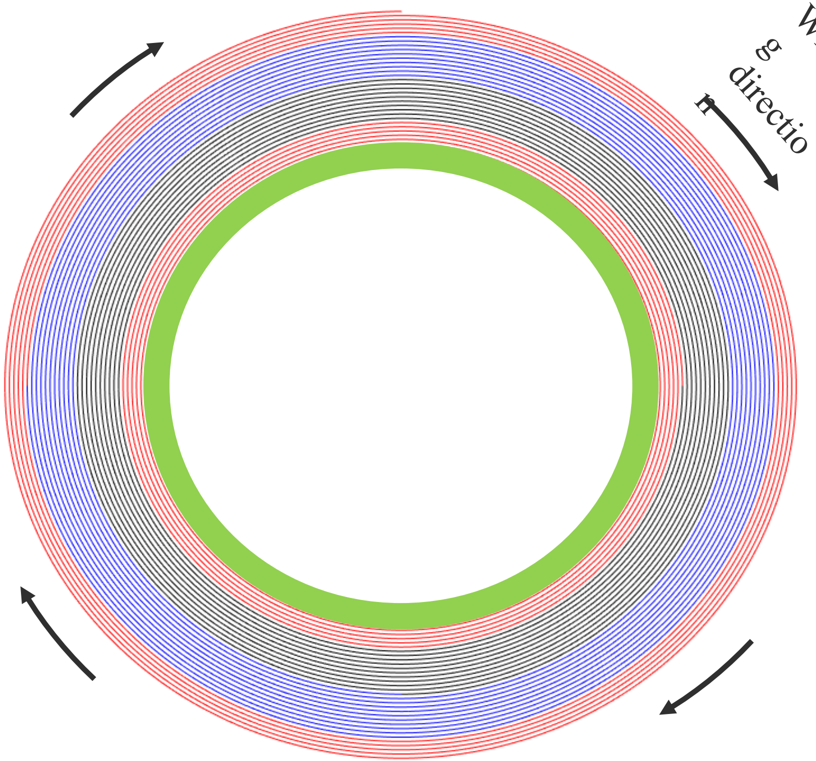


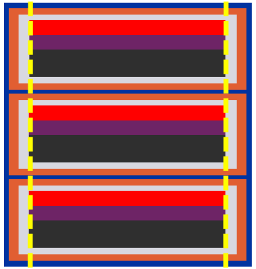
Different areas in pancake

- Mandrel (invar)
- Copper/Hastelloy tape (inner)
- HTS tape inwards
- HTS tape outwards
- Copper/Hastelloy tape (outer)

Joints

- Connections should handle 200°C during winding
- Spot welding Hastelloy/Hastelloy and gluing copper/copper are retained methods
  - Introducing local default
  - Is it mechanically fragile ?
- These steps can all be done before winding *(not necessarally preferably)*

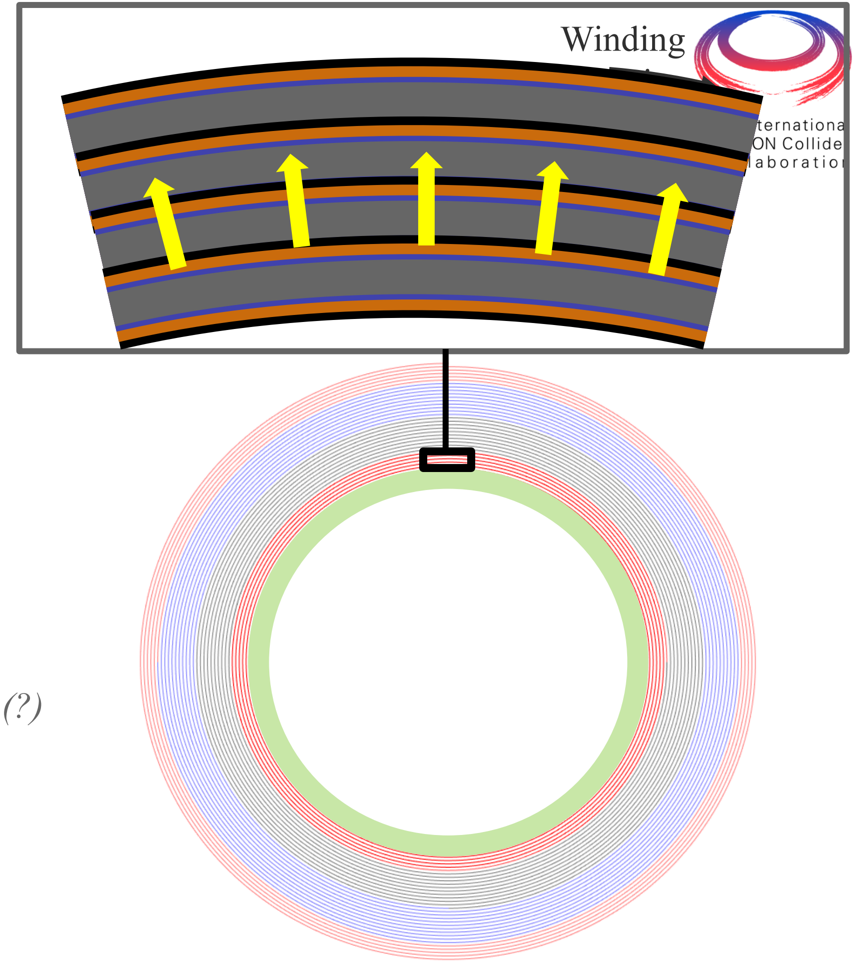




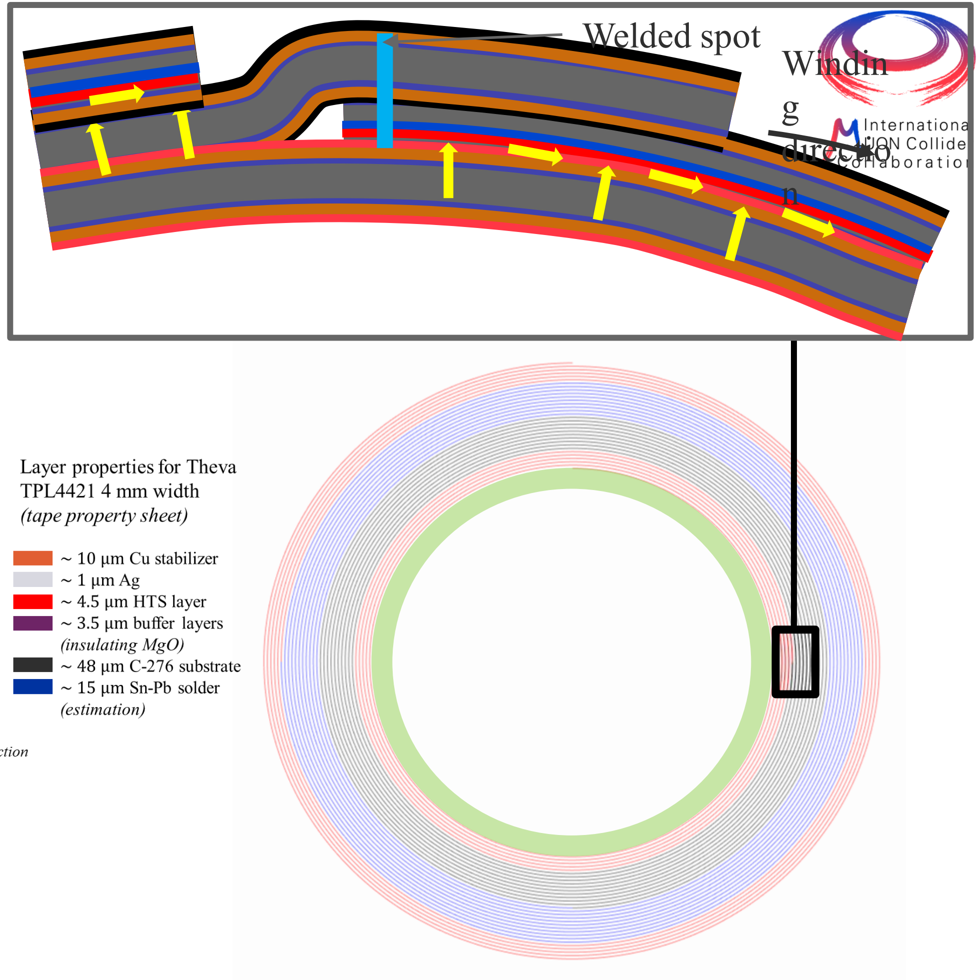
Layer properties for Theva TPL4421 4 mm width *(tape property sheet)*

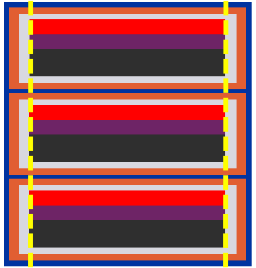
- ~ 10 µm Cu stabilizer
- ~ 1 µm Ag
- ~ 4.5 µm HTS layer
- ~ 3.5 µm buffer layers *(insulating MgO)*
- ~ 48 µm C-276 substrate
- ~ 15 µm Sn-Pb solder *(estimation)*

Scheme of tapes stack cross section



- First turns with hastelloy/copper tape (without HTS)
  - Redistributing stress
  - Electrical connection
  - **Calculations** to estimate n° of turns and acceptable stresses *(?)*
  - Resistance ~ 0.1 µΩ per turn





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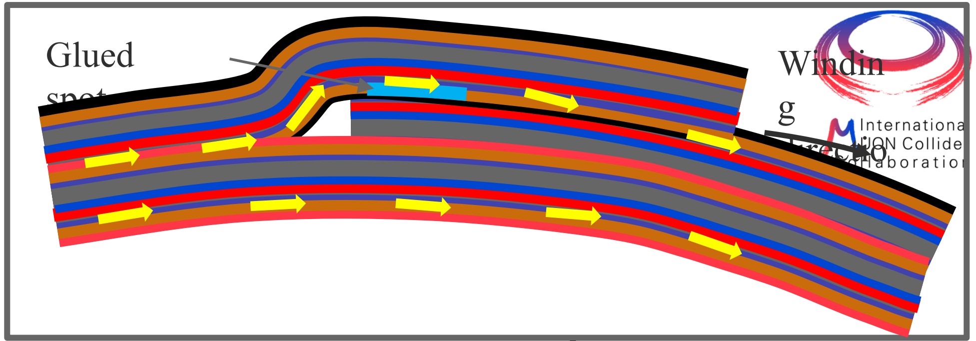
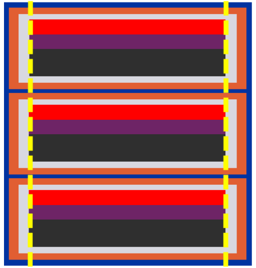
Scheme of tapes stack cross section

- Where to perform layer jump ?
  - At the begining to save material in case of failling ?
  - At lowest magnetic field location to reduce stresses ?
- Can be glued
- Resistance < 2 µΩ for 5 mm contact





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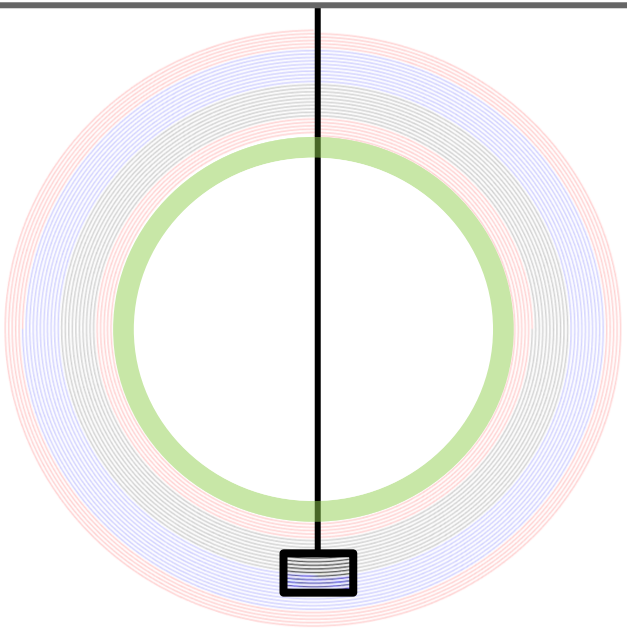
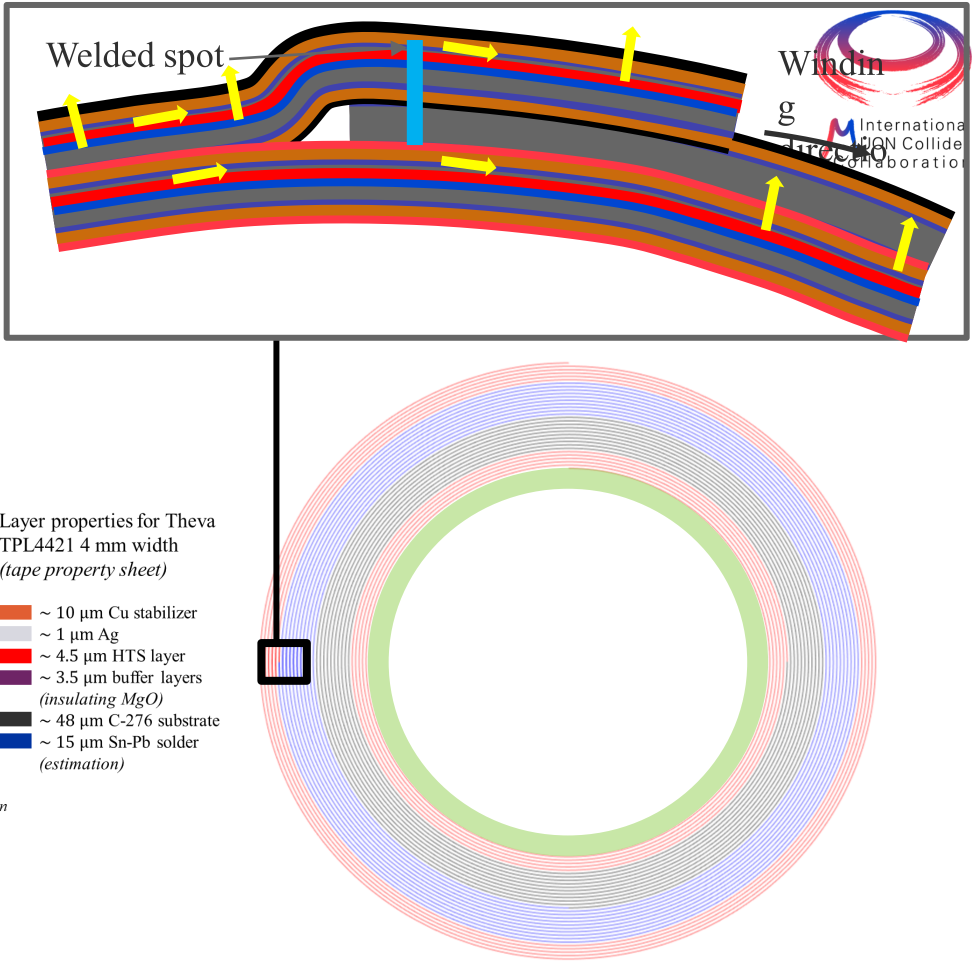
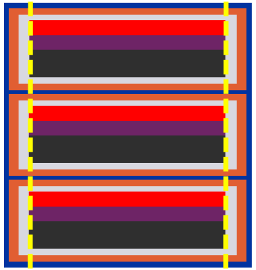
Scheme of tapes stack cross section



MuCol





Scheme of tapes stack cross section

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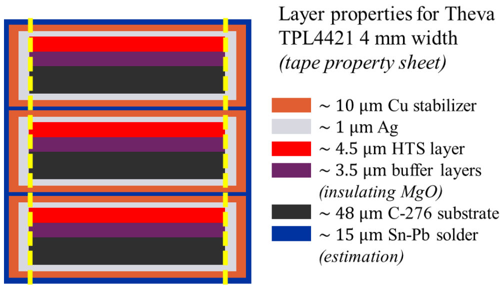
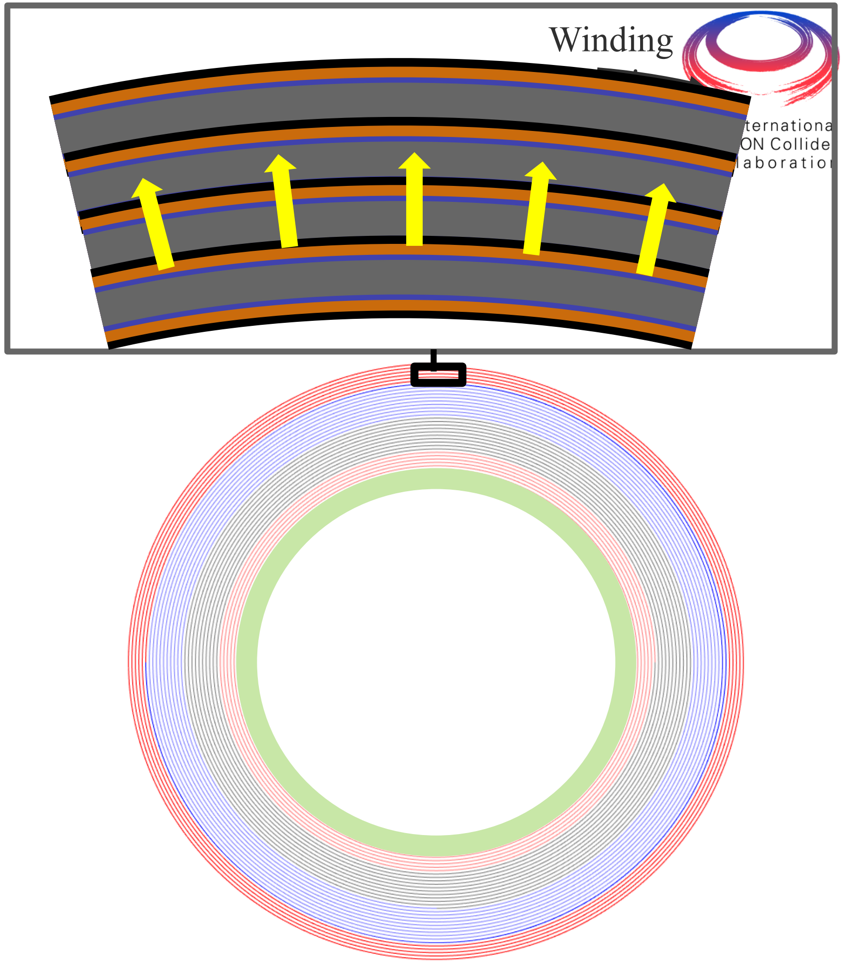
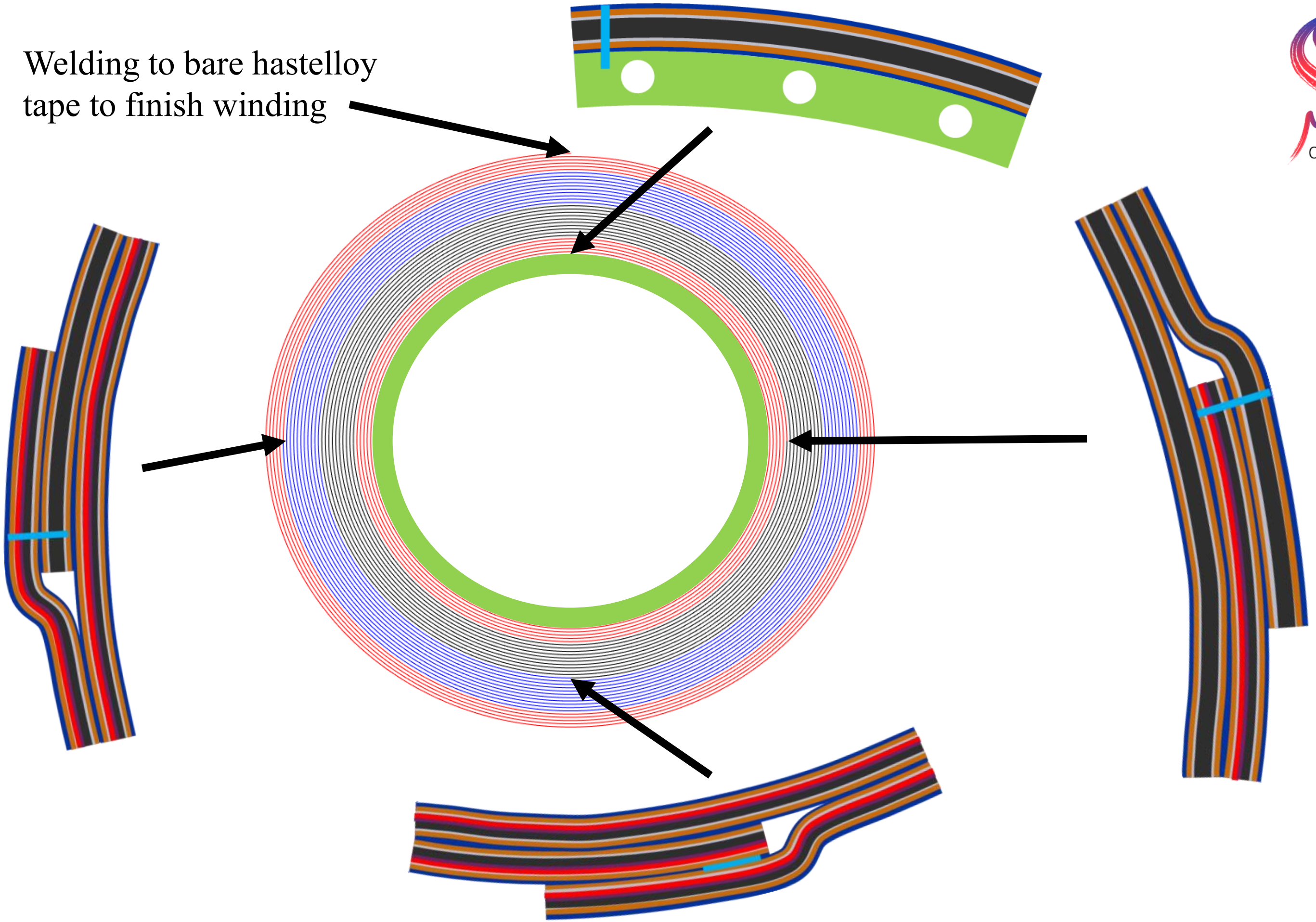
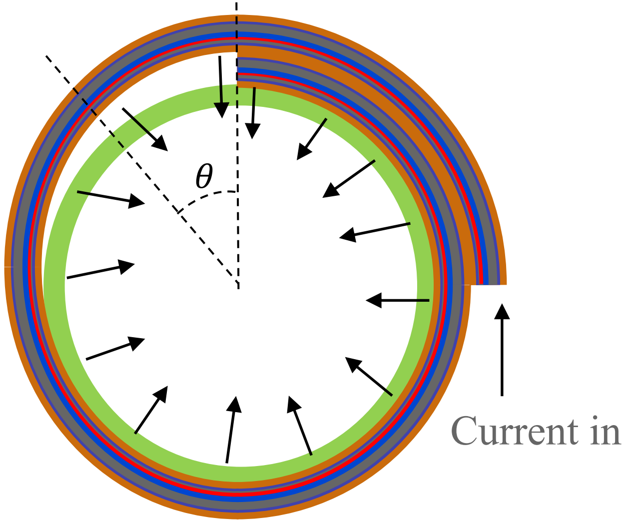


Scheme of tapes stack cross section

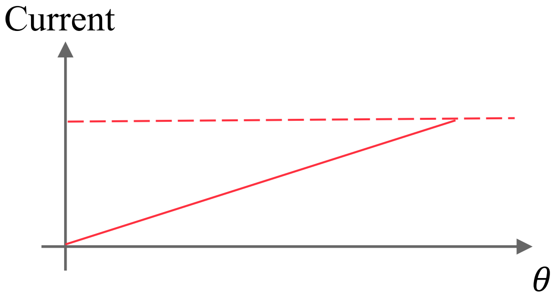


- Last turns with hastelloy/copper tape (without HTS)
  - Allow machining
    - For a deviation of 10 µm per tape → 1 mm per 100 turn
  - Electrical connection
  - Resistance ~ 0.2 µΩ per turn
- End of the winding with bare hastelloy tape
  - Removes the drop of solder
  - See the two last pancakes

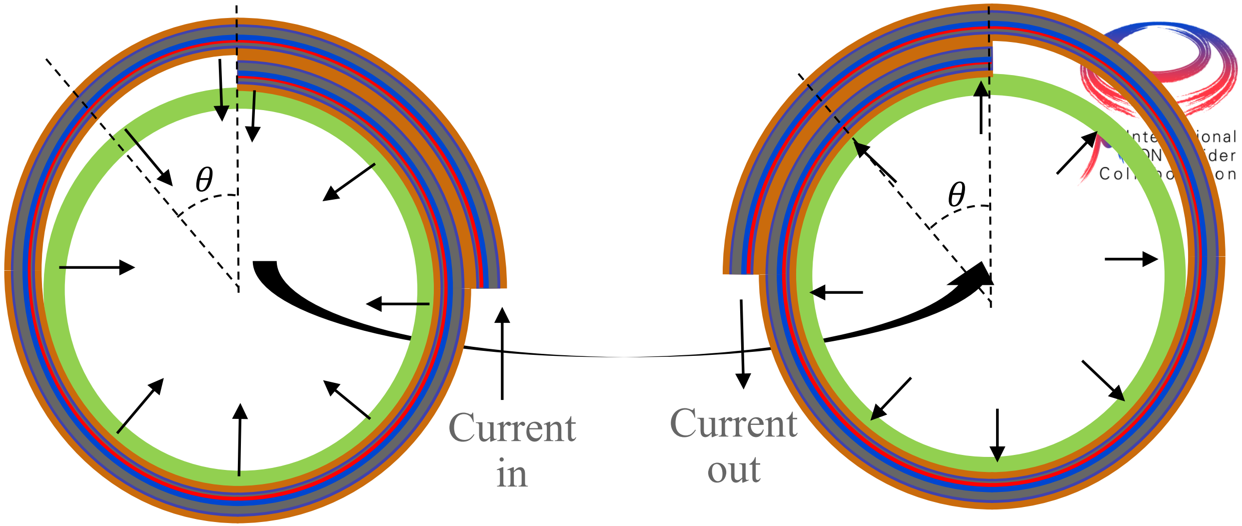

Welding to bare hastelloy
tape to finish winding

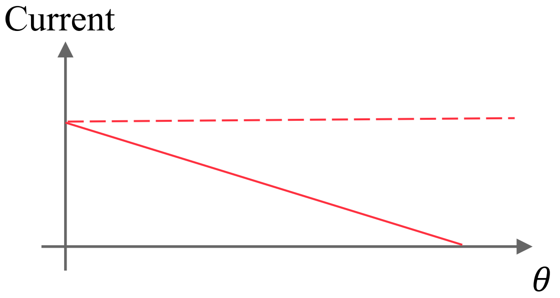


- Current flow *quasi* homogeneous in inner part
- Current flow linearly

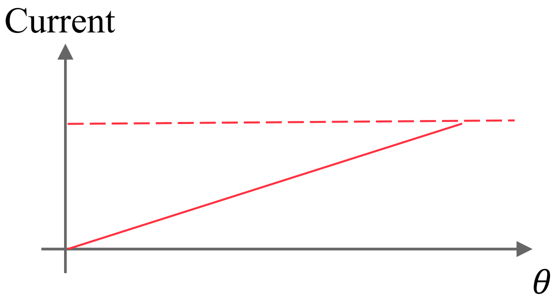


Last turn current flow





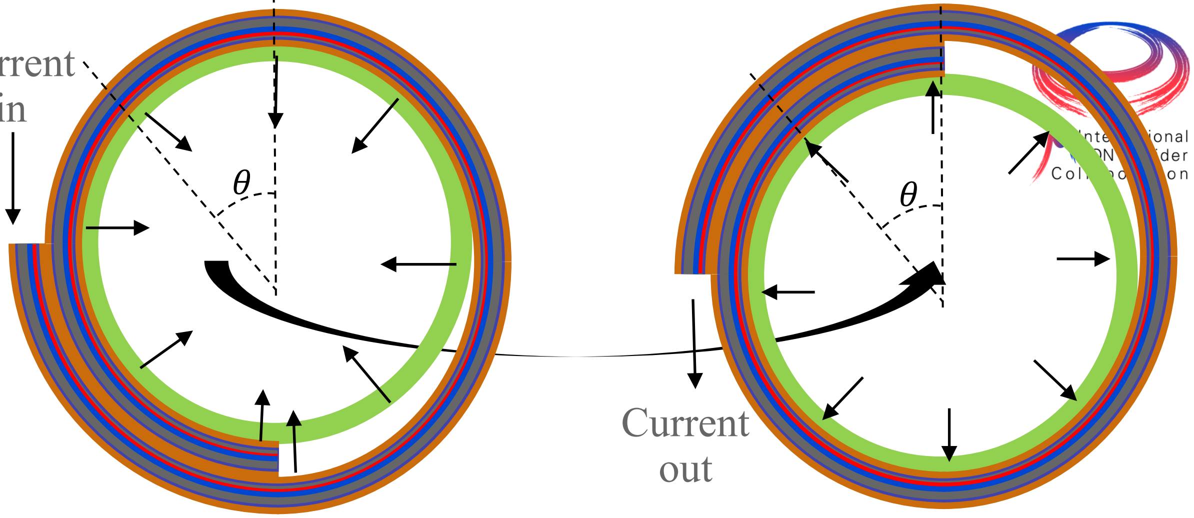
Last turn current flow

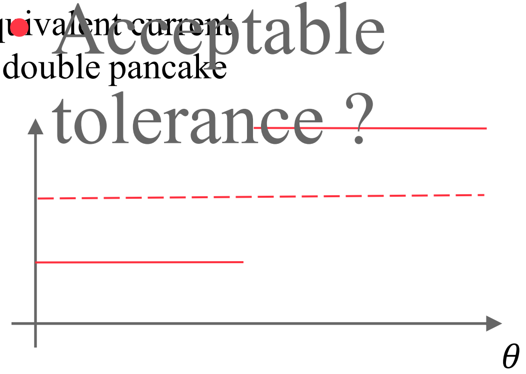


Last turn current flow

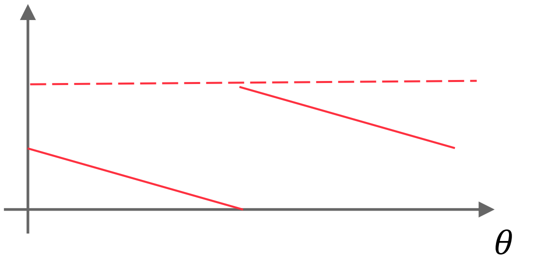
- Current flow *quasi* homogeneous in inner part
- Current flow linearly

- Issue for field homogeneity ?
- Acceptable tolerance ?

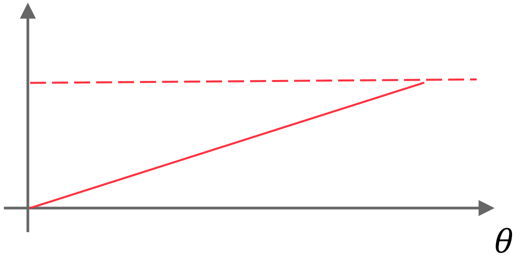




Last turn current flow



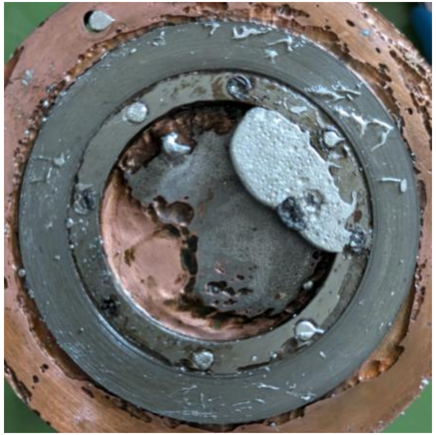
Last turn current flow



Last turn current flow

Etching

- Parts protected with silicon coating
- Whole pancake drowned into iron chloride
- Cleaned into sodium becarbonate
- Dried with pressurized air
- Cleaned with acetone
- Cleaned with water
- Dried with pressurized air

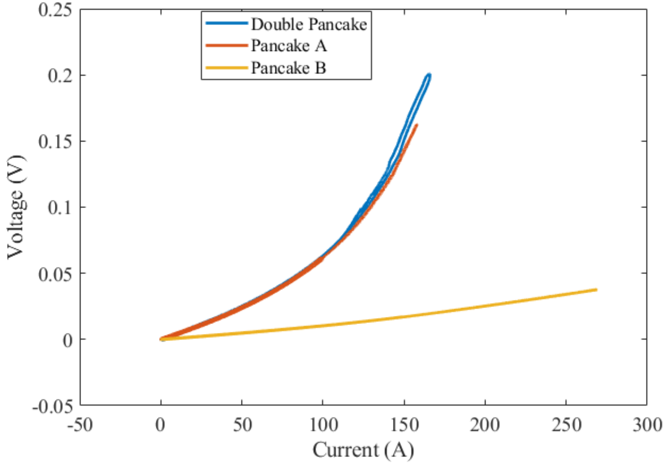


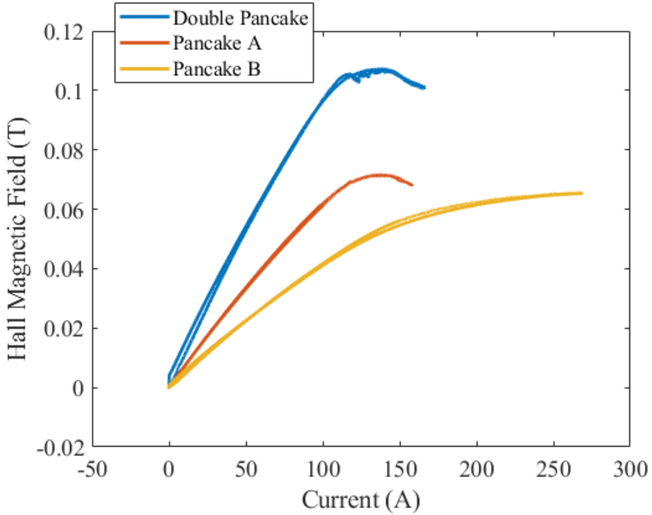
$\tau\ (s)$	Pancake 2	
	Charge	Discharge
5 A	4.87	4.92
10 A	4.70	5.05
20 A	4.78	5.02
50 A	4.60	4.83

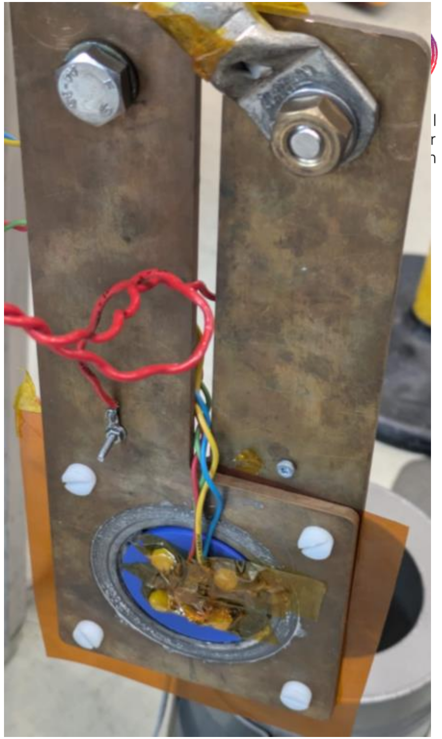
$\sim 4.8\ s$

$\tau\ (ms)$	Pancake 2 after etching			
	Charge	Discharge	Charge 2	Discharge 2
5 A	41.8	28.2	42.2	29.8
10 A	40.6	51.4		
20 A	30.4	43.1		
30 A	36.4	40.7	34.1	41.1
40 A	50.4	45.4	44.8	41.2
50 A	51.8	50.5		

$< 40\ ms$

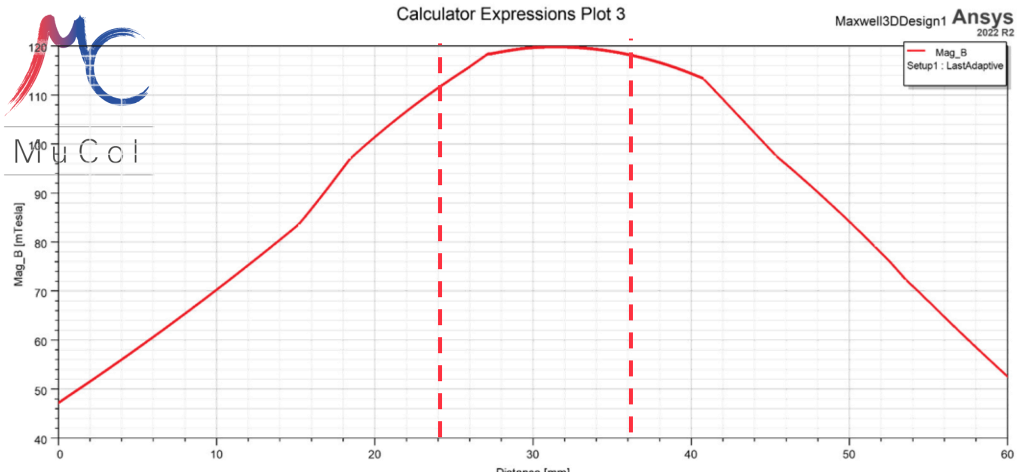


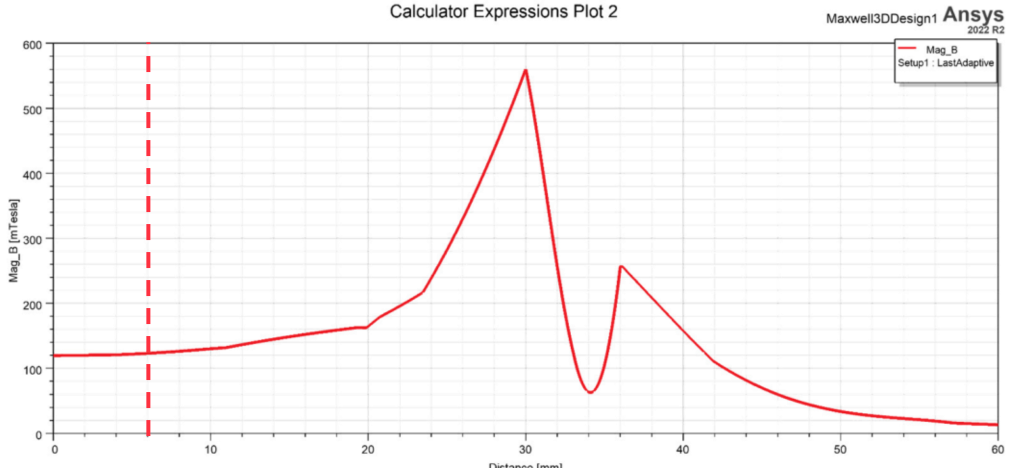


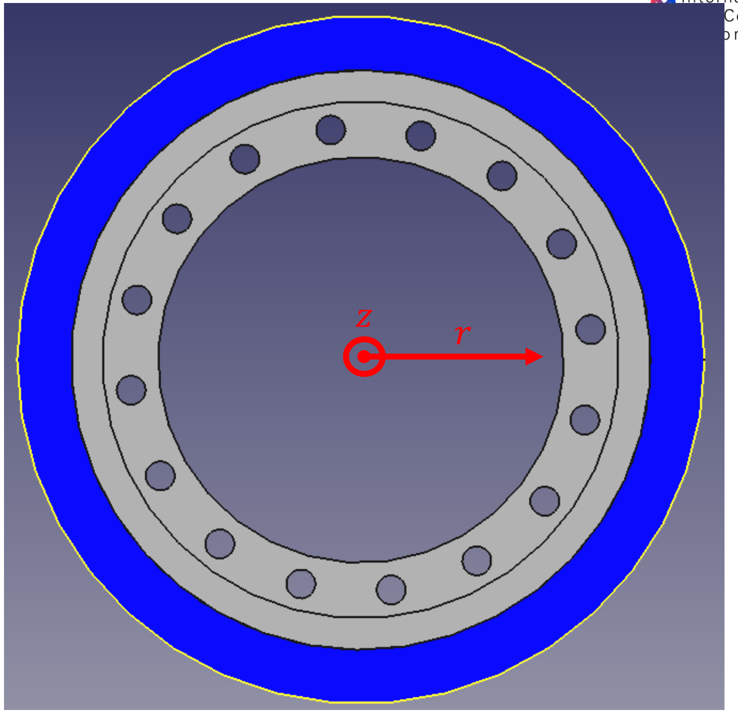


	Time Constant τ (s)
Double Pancake	4.6
Pancake A	1.6
Pancake B	3.1

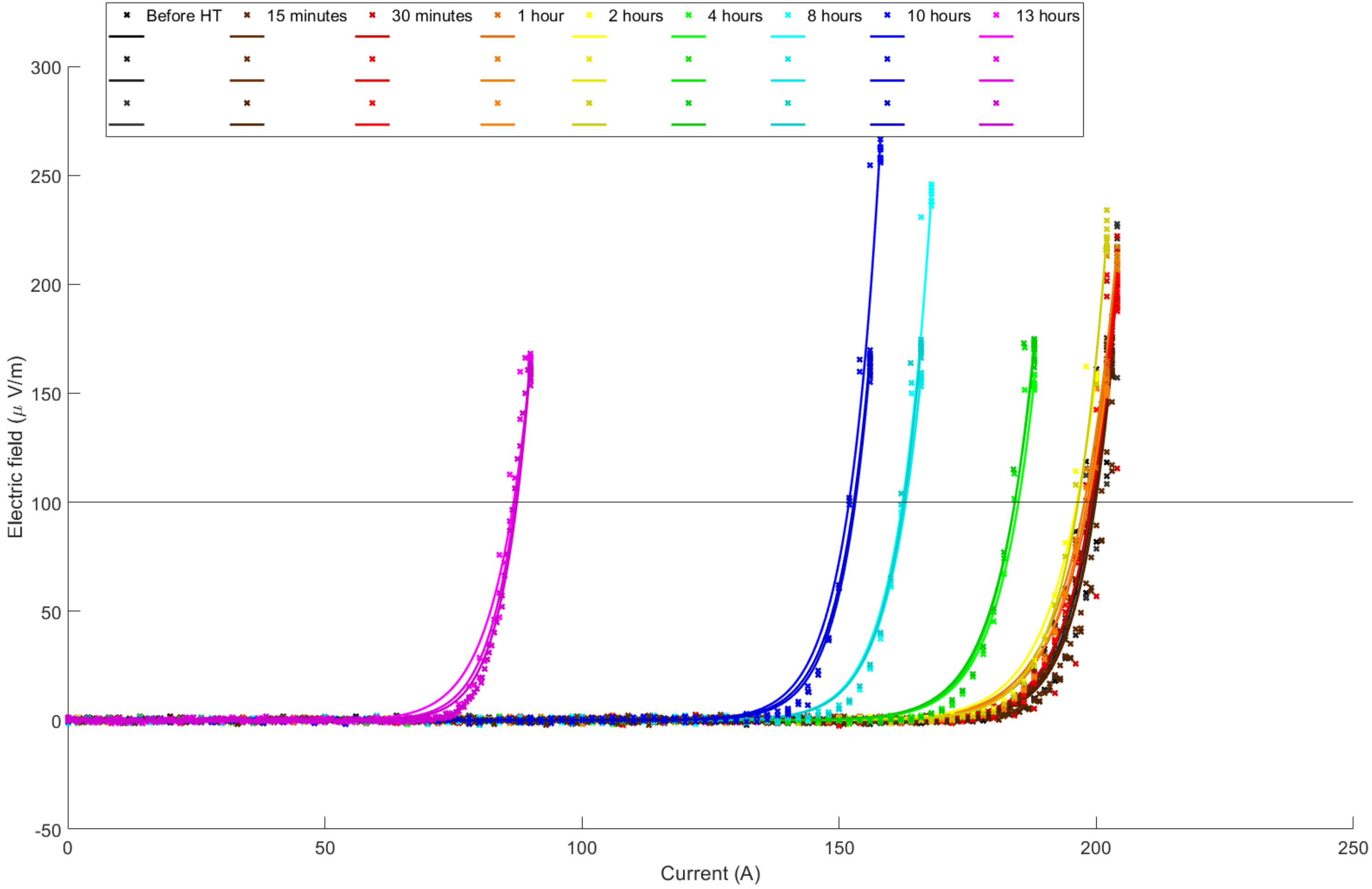
Where do these differences come from ?

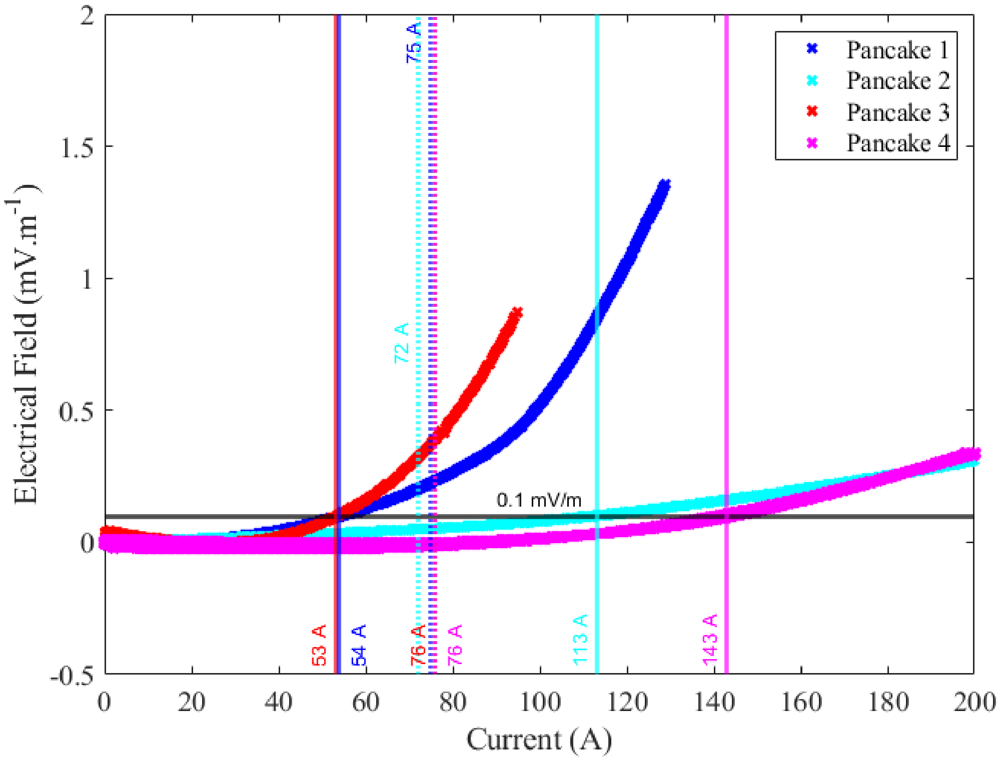






Variation ~10% of central field within ±5 mm from center


Before HT
15 minutes
30 minutes
1 hour
2 hours
4 hours
8 hours
10 hours
13 hours
300
250
200
150
100
50
0
-50
Electric field (μ V/m)
0
50
100
150
200
250
Current (A)



Pancake 1
Pancake 2
Pancake 3
Pancake 4
75 A
72 A
0.1 mV/m
53 A
54 A
76 A
76 A
113 A
143 A
Electrical Field (mV.m^{-1})
Current (A)